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GEOHYDROLOGY OF THE RAINY CREEK IGNEOUS COMPLEX NEAR
LIBBY, MONTANA

UNIVERSITY OF NEVADA, RENO

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University of Nevada

Reno

Geohydrology of the Rainy Creek
Igneous Complex Near Libby, Montana

A thesis submitted in partial fulfillment
of the requirements for the Degree
of Master of Science in Geological Engineering.

by

Ronald Eric Zinner

September , 1983

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To my parents.

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collection of field data.

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ABSTRACT

The Rainy Creek alkaline-ultramafic complex consists mainly of an ultramafic pluton crudely circular in plan view, composed primarily of magnetite pyroxenite, "vermiculite" pyroxenite, and biotite pyroxenite arranged in an inward succession.

"Vermiculite" pyroxenite is an alteration product of the biotite pyroxenite. The "vermiculite" pyroxenite has an average vertical extent between 150-200 ft., but minor amounts of good quality "vermiculite" have been found deeper.

The hydrological regime between the inner two pyroxenites is quite distinctive. The 150-200 ft. layer of "vermiculite" pyroxenite is composed mostly of weakly consolidated friable rock resembling a sandy type aquifer. The harder unaltered biotite pyroxenite contains water bearing shear zones, fractures, and joints.

Drill holes within the "vermiculite" pyroxenite produced up to 50 gpm while most holes encountering groundwater produced 10-25 gpm. Groundwater does appear to be controlled by impervious syenite dikes.

A pump and slug test in the "vermiculite" pyroxenite gave approximate values for transmissivity and hydraulic conductivity.

Weathering of the biotite pyroxenite by groundwaters

is concluded to be the major altering process but dilute hydrothermal fluids may have been responsible for a small amount of alteration.

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INTRODUCTION

Purpose and Scope

The "vermiculite" deposit near Libby, Montana is the largest known in the world and contains many atypical geological features. The deposit has received considerable geological, petrological, and geochemical attention since its discovery but the hydrological regime has been virtually ignored. This is ironic because many consider "vermiculite" genesis to be intimately related to the circulation of groundwater.

This is a geohydrological thesis study of the ultramafic and alkaline rocks comprising the Rainy Creek Igneous Complex. Because the hydrological properties of these rocks are unknown and since surface and groundwaters are considered to have played a major role in the ore genesis, a groundwater and surface water study was undertaken.

If the primary mechanism of alteration was the free circulation of groundwater then it is essential to know: the ability of water to migrate through the rock, the rock type affected, fluid chemistry, depth of accessibility or alteration, and the correlation of experimental laboratory data with field data.

Therefore, the purpose of this thesis study is to describe the geohydrology of the Rainy Creek area and

to propose an origin for the ore mineral "vermiculite". Hydrological questions have been focused on the Libby deposit because of its unusual vertical extent and it is hoped by the writer that this thesis might shed some light on these questions and promote further understanding of "vermiculite" deposits in general.

Method and Equipment

Work in the area was conducted during the summer months of 1981 and in January of 1982. Laboratory tests were made during Fall (1981) and Spring (1982) semesters. The writer also benefited from summer employment in 1981. Equipment and procedures for the study are the following:

Open standpipes - one-inch I.D. PVC Sch. 40 pipe was used for the four open standpipes. The standpipes were perforated 10 feet at the bottom with 1/4 and 1/8 inch holes to allow access of groundwater. The standpipes were backfilled with drill cuttings and were sealed with bentonite to section off the zone being measured.

Pumping well - four-inch I.D. PVC Sch. 40 casing was used for the pumping well. The bottom 10 feet were perforated with 1/8 and 1/4 inch holes and somewhat gravel packed.

Pump test equipment - for the pump test a 3/4 Hp. Teel pump was used. The pump was powered by a 5000 KW Onan portable generator. Black plastic pipe was used

to discharge the pumped water. The pumped water was directed away from the pumping area to assure no recharge within the radius of influence.

Slug test water - the water supply for the slug test was provided by a 1200 gallon water truck.

Water samples - water samples were collected by the writer and also by Montana Environmental Laboratory. Samples collected by the writer were taken with a homemade weighted and sealed plastic bailer. Samples were placed in 250 ml clean plastic bottles and were preserved with 5 drops of 10% hydrochloric or 5 drops of 10% nitric acid.

Scanning electron microscope - a scanning electron microscope was used for the qualitative platy mineral studies. The microscope used was an International Scientific Instruments Super III, interfaced with a Princeton gamma tech P.G.T. 1000 energy dispersive X-ray detector accurate to 0.1%. Samples were placed on copper tape and covered by a 5 A⁰ layer of gold.

Groundwater and whole rock analyses - the groundwater (collected from holes 131, 130, 96 and 74) and whole rock analyses were made by a commercial laboratory in Reno, Barringer Resources Inc. The whole rock analysis were made by total acid digestion and lithium metaborate fusion techniques and the water samples were analyzed by direct aspiration.

Preparation of samples for whole rock analysis and scanning electron microscope work - samples were prepared by hand picking 200-300 random grains individually under a binocular microscope or by the unaided eye. The grains were dry ground in a crucible to a 200 mesh size to assure representability of sample.

Previous Related Work in the Rainy Creek Area

Two early investigations of the Rainy Creek Complex were by J. T. Pardee and E. S. Larsen. Both visited the area several times between 1911 and 1927. Pardee and Larsen (1929) described the general geology of the intrusion and the surrounding Belt Series. Their paper included a thorough discussion on "vermiculite" and also a section on metalliferous minerals in the area. Gruner (1934) performed x-ray studies on twelve specimens under varying temperatures. He concluded vermiculite exists as a distinct mineral and used the name "hydrobiotite" when describing a molecular interstratification of biotite and vermiculite. In this thesis, the term "vermiculite" will be used where there is no distinction made between the minerals vermiculite and hydrobiotite. Barshad (1948) replaced naturally and unnaturally occurring ions in biotite and vermiculite. He analyzed products by x-ray, differential thermal analysis, and water loss and concluded that the kind of exchangeable ion determines the degree of expansion of the lattice, the

degree of hydration, and the nature of the differential thermal curves. Bassett's (1959) ion exchange experiments added to the hydrothermal studies of Roy and Romo (1957). Due to the unstability of vermiculite under hydrothermal conditions, Bassett concluded hydrobiotite and vermiculite were formed by supergene processes. Boettcher (1963-67) described the geology and petrology of the Rainy Creek Igneous Complex. He also continued the work of Roy and Romo (1957), Barshad (1948), Bassett (1959) and Weaver (1958) and proposed a weathering origin for the vermiculite and tentatively concluded that the hydrobiotite represents the attainment of homogenous equilibrium from hot dilute solutions. Other investigations of the area include Larsen and Hunt (1913), Goranson (1927), Kujawa (1942), Perry (1948), Larsen, Fletcher, and Cisney (1952), Alden (1953), Johns (1960), Beer (1960), and Weekes (1981).

Geography

The Rainy Creek Igneous Complex lies in the central portion of T 31 N, R 30 W, in Lincoln County, Montana (Figures 1 and 2). The largest towns in the vicinity are Libby, seven miles to the southwest and Kalispell, 90 miles to the southeast. The populations of Libby and Kalispell are approximately 8,000 and 56,000, respectively. The study area is accessible from Libby along Highway 37 and a paved access road.

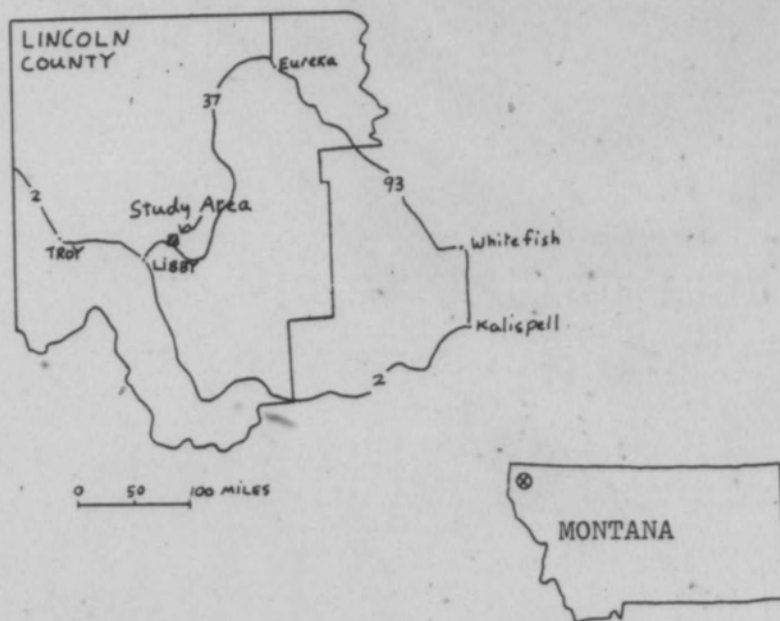


Figure 1. General location map of the study area.



Figure 2. AERIAL VIEW of the "VERMICULITE" mine.

The terrain is mountainous with dense forests and steep slopes. The major mountain ranges are the Cabinets to the southwest and Parcels to the northeast. The highest peaks in the vicinity reach altitudes of 7500 to 9000 feet (Johns, 1970).

The major watershed in the study area is the Rainy Creek Basin which drains into the Kootenai River approximately two miles to the south. The elevation at the mouth of Rainy Creek is 2080 ft. and the highest elevation in the mine area is 4234 ft..

Mean annual precipitation is approximately 18.47 inches with the mean wettest month being December. The mean seasonal snowfall is about 55 inches with the snowmelt beginning around March. Mean annual temperature is 45.1°F with the mean low occurring in January at 22°F and the mean high in July at 67.5°F.

The U. S. Forest Service, St. Regis lumber operations, the ASARCO Mine and the W. R. Grace "vermiculite" mine are the four biggest industries in the region. Recreational facilities include national parks, lakes, and skiing areas.

History of Mining in the Area

"Vermiculite" was not discovered in the Rainy Creek area until 1915. Prior to 1915 exploration interests in the area were confined to quartz veins in the search for base and precious minerals. B. M. Thomas, a geologist of

the time, discovered abnormal concentrations of vanadium in rock specimens collected. The high concentrations of vanadium were evaluated in greater detail when the demand for steel hardening metals increased during the first world war. While searching a small tunnel for vanadium mineralization, E. N. Allen of Libby accidentally discovered a platy-like mineral that exfoliated when heated by his candle flame. This mineral was found to be "vermiculite" and he and others soon incorporated to become the Zonolite Co.. Production of the ore body was initiated in 1925 but only 750 tons of "vermiculite" had been marketed by 1929. The "vermiculite" deposit was also being worked by companies such as Universal Insulation, Micalite Company, and Vermiculite and Asbestos Company. In 1929 the Zonolite Co. and Universal Insulation merged to form the Universal Zonolite Insulation Company which was then the sole producer of "vermiculite" in the area. In 1948 the name was changed to the Zonolite Company and in 1964 became the Zonolite Division of W. R. Grace & Co.. W. R. Grace is a large U. S. firm whose "vermiculite" interests at Libby, Montana and South Carolina make up only a small part of their revenue. The mine is currently run under the Construction Products Division of W. R. Grace & Co., with headquarters in Cambridge, Massachusetts.

REGIONAL GEOLOGY

Stratigraphy

The Rainy Creek ultramafic complex intruded meta-sedimentary clastics and carbonates of the Belt Series (Johns, 1970). The late Precambrian sediments have undergone low grade regional metamorphism of the greenschist facies. The thickness of the belt series cannot be determined since the bottommost stratum is not exposed and the top is an erosional surface. However, in the western part of Lincoln County the rocks have been estimated to be in excess of 39,000 ft. (Johns, 1970). The belt series has been divided into the following units: (Johns, 1970)

Libby Formation - grey and green argillites, sericitic argillites, calcareous argillites, sandstone, minor shale and limestone. 7600 + ft. thick.

Striped Peak Formation - thin bedded ferruginous and sericitic dark red-purplish sandstone and quartzite. 4500 ft. thick.

Wallace Formation - green, grey calcareous and sandy argillite, containing dark and light colored laminae, quartzite and sandstone interbedded with argillite. Limestone and dolomite show molar tooth structure in middle Wallace stratum. 15,000 + ft. thick.

Ravalli Group - medium grey, bluish grey, and white quartzites, and quartzitic argillites. Variable amounts of magnetite distributed throughout. Biotite and pyrite

also present. 7070 ft. thick.

Prichard Formation - grey, brown, blue-green, green-brown argillites; sparse sandy horizons and quartzite beds are present. Fine biotite and sparse pyrite occur throughout. A distinctive banding occurs in the upper beds, the formation is medium and thick bedded throughout. 9700 + ft. thick.

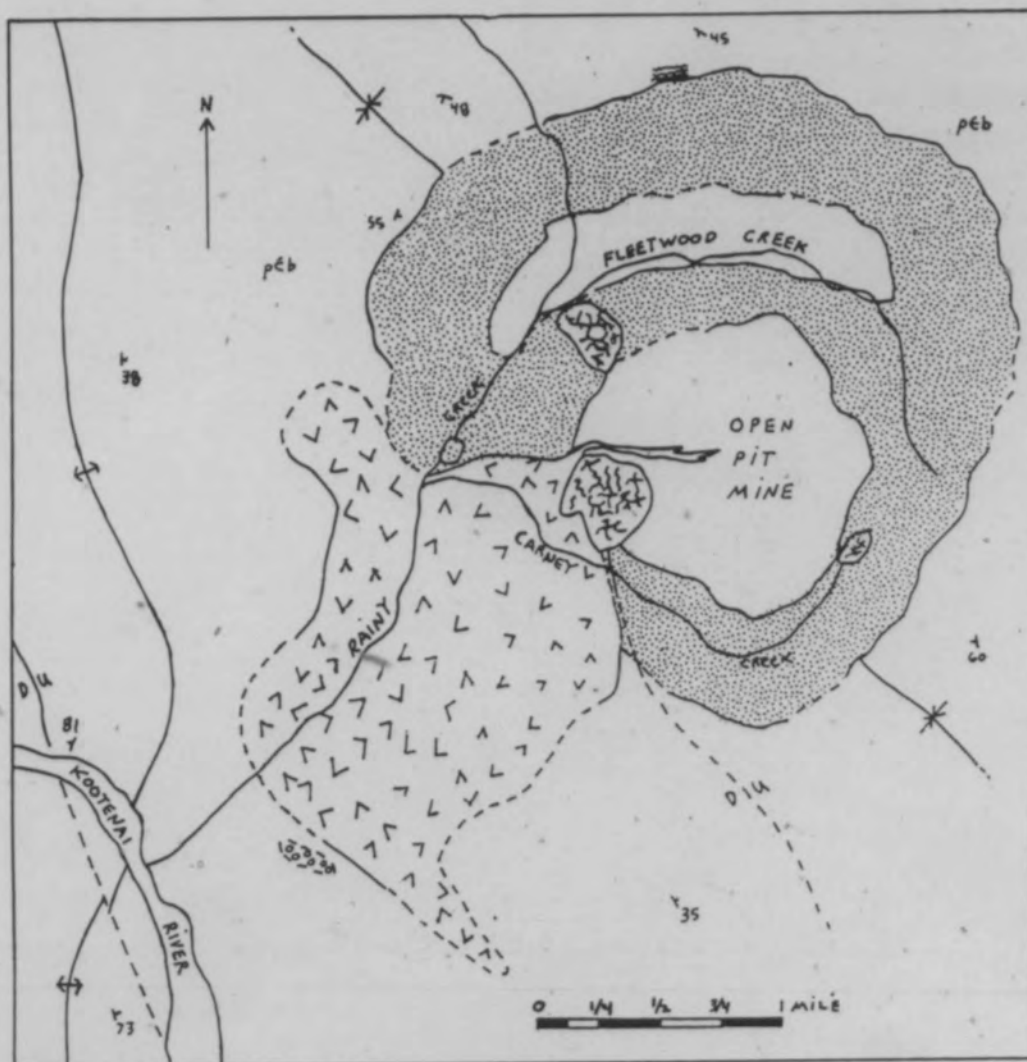
Structure

The belt series in the vicinity of Rainy Creek has been folded and faulted in a north-northwesterly direction. There is a major fault and major fold within the study area. The fold is a broadly plunging asymmetric syncline with limbs dipping east and west, parallel to the strike of the Wallace and Striped Peak formations. The fault is poorly exposed near Carney Creek and is a high angle reverse fault with relative movement down on the west side. The Rainy Creek intrusion does not appear to be genetically related to the faults or folds (Boettcher, 1966).

GEOLOGY OF THE RAINY CREEK INTRUSIVE

The Rainy Creek Igneous Complex is the largest of its kind in the region. An ultramafic pluton crudely circular in plan view comprises the majority of the complex (see figure 3). Exposed in the center of the pluton is biotite pyroxenite surrounded by "vermiculite" pyroxenite that contains the ore mineral "vermiculite" (see figure 4). The "vermiculite" pyroxenite is an alteration product of the biotite pyroxenite. Surrounding most of these inner pyroxenites is a large body of magnetite pyroxenite that forms dikes within the "vermiculite" and biotite pyroxenites. A large alkali syenite body lies along the southwest side of the complex and extends as vertical dikes into the biotite pyroxenite. A small body of nepheline syenite lies about 500 ft. southwest of the large syenite body (Boettcher, 1966). Many dikes of all sizes, including magnetite pyroxenite, alkali syenite, trachyte-phonolite clans, alkaline pegmatites, alkali granite, and late stage quartz and calcite veins cut all of the earlier rocks. Hydrothermal activity has altered the pyroxene to tremolite, hornblende, and possibly biotite. Glacial deposits, lacustrine sediments, and slope debris are found covering most of the rocks where mining has not removed them.

From field relationships the age of the Rainy Creek intrusive can only be catagorized from post-later Precambrian










-  Mine Waste and Mill tailings
-  Nepheline syenite
-  Syenite
-  Magnetite pyroxenite
-  Fenite
-  Biotite and "vermiculite" pyroxenite-undivided,
See Figure 3
-  Belt Series

Figure 3. Geology of the
Rainy Creek
District.
(Boettcher 1966)

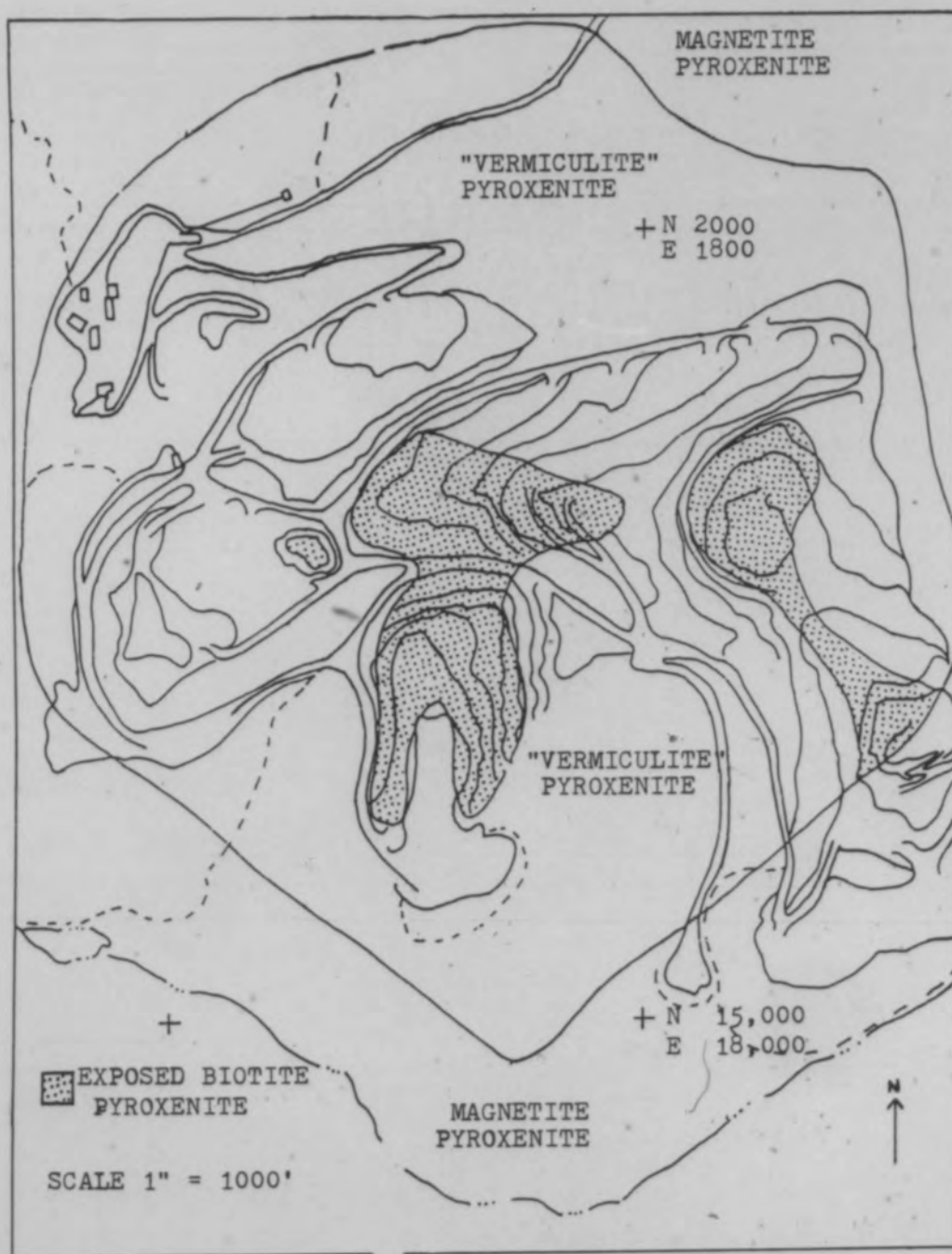


Figure 4. Map showing exposed biotite pyroxenite.

to pre-Pleistocene. However radiometric dating of fresh biotite from the biotite pyroxenite has given an age of 104 million (± 3) years thus making the Rainy Creek Complex pre-Laramide in age (U.S.G.S. 1982).

Biotite Pyroxenite

The biotite pyroxenite is exposed along the crest of Vermiculite Mountain and also at lower elevations where mining has removed the "vermiculite" pyroxenite ore body. At present this biotite pyroxenite covers approximately .5 square miles and will increase as mining continues. Because of the nature of alteration, the biotite pyroxenite-"vermiculite" pyroxenite contact is fairly constant with depth and reflects the slope of the land surface before mining began.

The mineral content of the biotite is highly variable. Some outcrops contain almost pure biotite with feldspar making up most of the remainder while in other areas almost pure pyroxene is not uncommon. Recent deep drilling in the biotite pyroxenite shows this relationship to be true at depth. Tremolite also occurs but is not nearly as conspicuous as that found in the "vermiculite" pyroxenite discussed in the next section.

Previous studies of the Rainy Creek intrusive referred to this biotite pyroxenite zone as "biotitite" consisting of coarse grained biotite with minor feldspar and calcite. The writer observed a variable amount of pyroxene in this zone

as stated above and is referring to this rock type as "biotite pyroxenite" consistent with the terminology currently used by the W. R. Grace mining staff. The discrepancy may be partially attributed to limited exposures available for the previous studies.

The biotite pyroxenite has a highly variable grain size, and is hard, unlike the surrounding friable ore body. This biotite pyroxenite was protected from the alteration mechanism responsible for the conversion of biotite to "vermiculite" in the surrounding pyroxenite. A detailed discussion as to why the biotite was not altered is given in the last section of the thesis.

"Vermiculite" Pyroxenite

The "vermiculite" pyroxenite body covers 2.5 square miles and contains the economic deposits of "vermiculite" presently being mined. The average vertical extent of the "vermiculite" pyroxenite is between 150-200 ft. with the "vermiculite" then grading over a narrow zone into biotite.

Most of the "vermiculite" pyroxenite is friable, fractured, easily drilled and can be crushed into individual grains within the hand, some porphyritic pyroxenite also exists. The porosity and permeability would appear to be as high as that of a weakly consolidated sandstone.

Diopside, "vermiculite", tremolite, accessory apatite, and trace biotite make up most of the "vermiculite" pyroxenite.

Mineral proportions are variable, particularly in a lateral direction, but on the average, diopside is the dominant mineral. The average content of "vermiculite" is approximately 12 percent by weight on a +65 mesh basis. Tremolite is disseminated in low concentrations throughout the pyroxenite body. The tremolite occurs in higher concentrations as conspicuous light colored tabular masses and as veins and stringers. Apatite at the Rainy Creek Complex is associated with the "vermiculite". This association is not limited to this area and has been reported at other "vermiculite" deposits. Unaltered biotite is only found in small concentrations within the "vermiculite" pyroxenite. Boettcher (1966) reported the optical properties of the unaltered biotite in the "vermiculite" pyroxenite to be the same as in the biotite pyroxenite (Table 1). Irregularly shaped pyroxenite bodies or blocks are found within the main "vermiculite" pyroxenite. These bodies could possibly be related to the broken nature of the rest of the "vermiculite" pyroxenite. Boettcher (1966) has suggested the tabular or irregularly shaped bodies result from late surges of volatile rich magma.

Magnetite Pyroxenite

Magnetite pyroxenite encloses the "vermiculite" pyroxenite and biotite pyroxenite and borders the Belt Series, except where it is truncated by the large alkali syenite body. The magnetite pyroxenite covers more surface area

than any other ultramafic body in the area. Boettcher (1966) believes the magnetite pyroxenite was emplaced as a large ring dike into a weak zone surrounding the earlier intrusions. Veins of magnetite pyroxenite have intersected the earlier rocks all the way to the biotite pyroxenite core. The magnetite pyroxenite is less resistant than the "vermiculite" pyroxenite and is responsible for the domal shape of Vermiculite Mountain and surrounding creeks in the magnetite pyroxenite zone.

The minerals in the magnetite pyroxenite are finer grained than the previous intrusions and are comprised chiefly of augite and magnetite with "vermiculite", biotite, garnet, and sphene making up the accessory minerals. Limited evidence in a deep hole drilled during the summer of 1981 suggests biotite alteration to "vermiculite" is similar to that in the "vermiculite" pyroxenite with biotite not encountered until about 150 feet. This recent deep drilling within the magnetite-pyroxenite zone also indicated that very minor amounts of good quality "vermiculite" existed below 150 feet.

The contact between the magnetite pyroxenite and the belt series is not easy to distinguish. Boettcher (1966) reports the contact occurs where there is a slope increase, a change in vegetation, or seeps. A fenitization zone approximately 250-350 feet wide occurs at this contact forming minerals such as aegirine, augite, and sodic actinolite.

Alkaline Syenite and Nepheline Syenite

An irregularly shaped mass of syenite 2.1 square miles in area forms the southwest portion of the igneous complex. Boettcher (1966) believes the alkali syenite was probably altered from nepheline syenite with a subsequent change from nepheline to muscovite. An apophysis of this body intrudes in an east-west direction into the center zone of biotite pyroxenite. A small body of unaltered nepheline syenite less than .5 square miles in area is found southwest of the main syenite mass. The syenite is composed of microclitic microperthite with 20-30% muscovite (Boettcher, 1966).

Dikes and Veins

A variety of dikes and veins cut the rocks in the Rainy Creek Complex. Steeply dipping northwest and northeast trending syenite dikes commonly cut the ultramafic and metasedimentary rocks in the area. Horizontal syenite dikes are also found in the mine area.

Also present at the complex are dikes of porphyritic alkali trachyte and porphyritic rhyolite. The porphyritic alkali trachyte is more common than the porphyritic rhyolite.

The late stage development was that of quartz and calcite vein intrusion. Tremolitization of pyroxene from the emplacement of the quartz and calcite veins is widespread

throughout the mine area.

Geologic Evolution of the Igneous Complex

The following summarizes the geologic evolution proposed by Boettcher (1966). The Rainy Creek alkaline-ultramafic Complex is a composite of successive igneous intrusions emplaced into the Precambrian metasedimentary rocks of the Belt Series, probably in middle Cretaceous time. First to be emplaced was the circular shaped body of biotite pyroxenite considered to have formed from the accumulation of alkalis and volatiles at the roof of the pyroxenite pluton. Next, magnetite pyroxenite intruded a zone of weakness, probably as a ring dike between the biotite pyroxenite and the belt series. Dikes of magnetite pyroxenite transect the inner pyroxenite. The ultramafic rocks are thought to be products of fractional crystallization of a common parent magma. After the emplacement of the ultramafic rocks a large body of syenite intruded the southwestern part of the ultramafic pluton extending all the way to the inner pyroxenite. The last sequence involved the intrusion of numerous dikes and veins including alkaline dikes, phonolite dikes, trachyte dikes and quartz and calcite veins. Associated hydrothermal activity altered adjacent pyroxene to fibrous tremolite.

HYDROLOGY

Surface Water

The major watershed near the mine is the Rainy Creek drainage basin. Rainy Creek is a tributary of the Kootenai River which forms part of the upper Columbia River drainage system (Johns, 1970). There are few surface water bodies in the Rainy Creek drainage system. A tailings pond, fresh water pond, and a reroute pond were constructed as part of the closed water system to the mill. In addition there are a few springs scattered throughout the study area.

Rainy Creek flows in a southerly direction until it reaches the Kootenai River near the "vermiculite" screening plant. The elevation of Rainy Creek varies from 2080 feet at its junction with the Kootenai River to 5000 feet at its headwaters between Blue Mountain and the north fork of Jackson Creek. Mountain slopes range from 5200 to 3200 feet. Valleys and gorges are approximately 1000 feet wide. The area drained is 17.8 square miles and has previously been subdivided into five separate areas listed below. (Bovay Engineers, 1971) :

<u>Drainage Basin</u>	<u>Area</u>
Upper Rainy Creek	5.9 square miles
Central Rainy Creek	5.6 square miles
Lower Rainy Creek	.3 square miles
Fleetwood Creek	3.8 square miles
Carney Creek	2.2 square miles

Total Rainy Creek Drainage = 17.8 square miles

The only streamflow records found by the writer in the Rainy Creek drainage system are reported by Bovay Engineers (1971). The records are from a gauging station run by the U. S. Forest Service located in the northwest quarter of the northwest quarter of section 22, township 31 north, range 30 west (the Forest Service currently has no record of these flow rates, oral communication). The records were kept from April 10, 1964 to June 21, 1968. The records show a maximum flow of 7372 gpm on June 16, 1965 and a minimum flow of 404.6 gpm. Bovay Engineers (1971) report that the Forest Service did not guarantee the accuracy of these measurements. Measurements by persons working in the area give a maximum value of 7000 gpm and a minimum value of 25 gpm at the junction of Fleetwood and Rainy Creeks (Bovay Engineers, 1971).

Bovay Engineers (1971) computed the theoretical maximum volumetric flow rates to be expected in the Rainy Creek Basin. The formula used was the Burkli-Ziegler formula (Chow, 1964):

$$Q = MR^C \sqrt[4]{S/M},$$

where c = coefficient of runoff = 0.1 ; R = rainfall intensity = 0.8 ; S = slope ; and M = drainage area in square miles.

The results of the analysis are shown in Table 2. These calculated flow rates, based on a fifty year storm, are as high as 404,100 gpm which are much higher than any known floods in the area. Bovay Engineers (1971) explained this discrepancy by stating that water probably infiltrates rather quickly into the subsurface. The surface layer in the valley of the Rainy Creek Basin is an average of five feet thick and is composed of soft and weak silty alluvial material. Underlying this top layer are fine to coarse grained gravels that are 20 to 25 feet thick and serve as an aquifer. Test holes in this area quickly filled up with water to within two feet of the surface. It was not stated whether the tests followed a rain or not. Gravels and highly permeable pockets were encountered in the construction of the tailings dam in central Rainy Creek that warranted supplemental dam design consideration. The slopes above the valley are covered with an organic debris layer underlain by slope debris and glacial deposits.

Because the theoretical values were so much higher than known values Bovay Engineers (1971) plotted a graph of maximum flow rate versus drainage area for other drainage basins in the area. They were able to construct a curve through these points and interpolated a maximum of 161,000 gpm

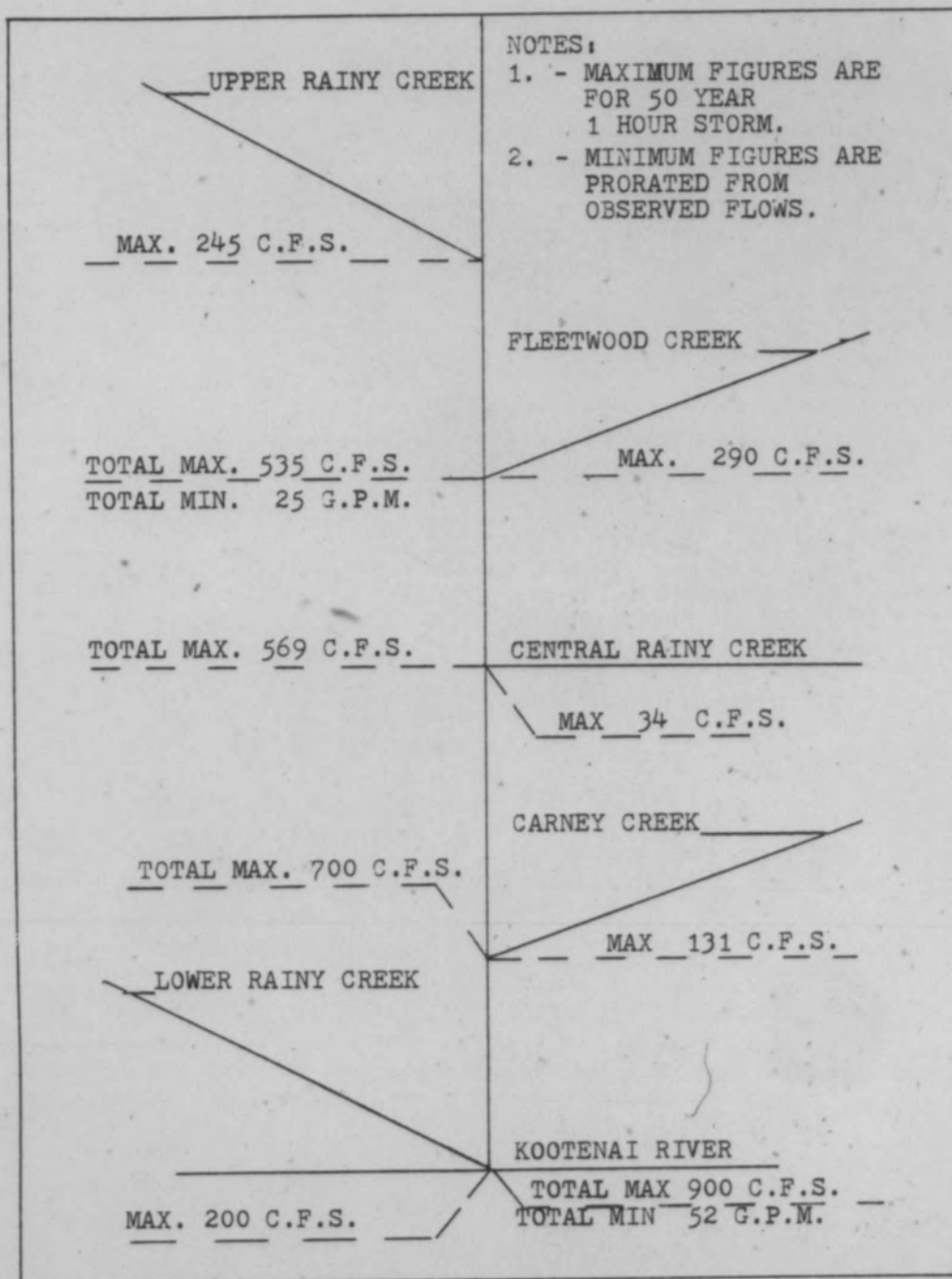


Table 2. Rainy Creek Drainage Basin
Schematic flows theoretical.
(Bovay Engineers, 1971)

for the Rainy Creek Drainage Basin using an area of 17.8 square miles (Figure 5).

The above values were only meant to show the reader what surface water data was available. Because none of the above information is based on substantiated measurements in the Rainy Creek basin no conclusions can obviously be drawn.

Groundwater

Introduction

Groundwater is a term usually limited to that subsurface water found below the water table. Neglecting a narrow saturated zone above the water table called the capillary fringe, the water table can be thought of as the boundary between the unsaturated zone and the saturated zone.

The majority of water in the saturated zone is found in porous and permeable media referred to as aquifers. Impermeable and semi-permeable zones separating different aquifers are termed aquicludes and aquitards, respectively.

The water or fluid in an aquifer is usually dynamic in space and time. The aquifer or water bearing zone is part of the hydrologic cycle and through this cycle is recharged or replenished from rainfall or snowmelt. The rainfall or snowmelt infiltrates through the unsaturated zone until it reaches the water table. Water discharges from the aquifer as baseflow to streams, springs, evaporation through the unsaturated zone, or, in some cases, as transpiration.

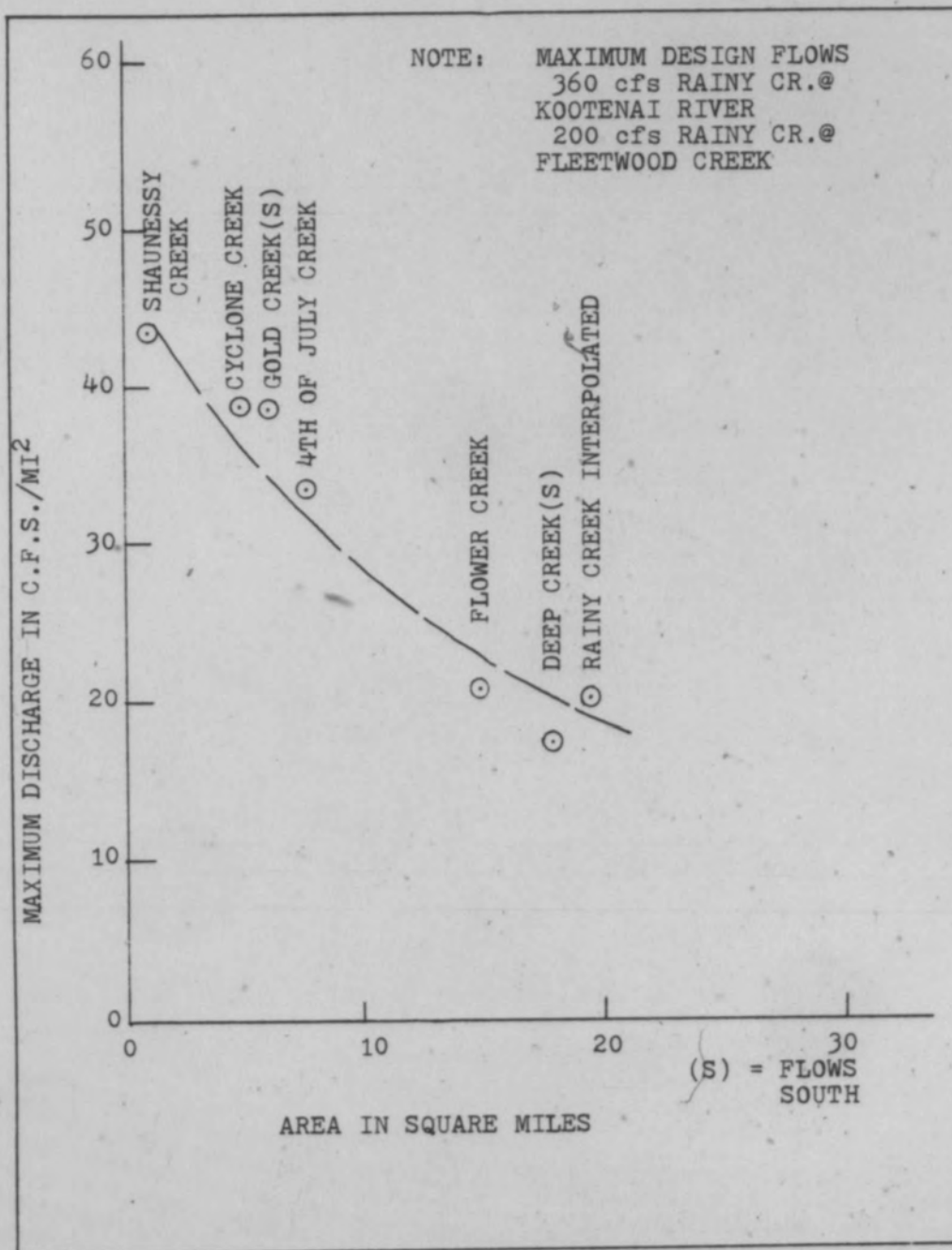


Figure 5. Discharge versus drainage area for other drainage basins in the area. (BOVAY ENGINEERS, 1971)

The force driving water through a porous or fractured medium is the fluid potential or the mechanical energy per unit mass of fluid. The fluid potential can be expressed by the Bernoulli equation:

$$\phi = gz + \frac{v^2}{2} + \int_{P_0}^P \frac{dP}{\rho},$$

where g = acceleration due to gravity ;

z = elevation above an arbitrary datum ;

V = velocity ;

P = pressure ;

P_0 = atmospheric pressure ; and

ρ = density of fluid.

Assuming that the fluid density is constant and taking $P_0 = 0$ (gage pressure), the above equation becomes:

$$\phi = gz + \frac{v^2}{2} + \frac{P}{\rho}.$$

In groundwater hydrology, hydraulic head (the mechanical energy per unit weight = ϕ/g) is commonly used instead of potential. Thus, the above equation can be expressed as :

$$\frac{\phi}{g} = h = z + \frac{v^2}{2g} + \frac{P}{\rho g}$$

Since ground water flow velocities are generally very low, the velocity head ($v^2/2g$) is generally negligible compared to the sum of the elevation (z) and pressure ($P/\rho g$) heads. The equation for hydraulic head then becomes :

$$h = z + \frac{P}{\rho g} = h_z + h_p,$$

where h = hydraulic head (L) ;
 h_z = elevation head (L) ; and
 h_p = pressure head (L).

Figure 6 shows the relationship for an open standpipe.

Groundwater flows from high hydraulic head to low hydraulic head. Knowledge of the hydraulic head distribution h , along with other information, enables the calculation of Q , the volumetric flow rate. This can be accomplished by utilizing Darcy's Law:

$$Q = \frac{-KA(h_2 - h_1)}{L},$$

where K = hydraulic conductivity (L/T) ;
 A = cross-section area of flow (L²) ;
 h = hydraulic head (L) ; and
 L = distance along flow line (L).

The hydraulic conductivity is a function of the properties of the medium and the fluid passing through it. This parameter may vary in direction from a point as well as throughout space. Darcy's Law written in terms of the specific discharge q is :

$$q = \frac{Q}{A} = \frac{-K(h_2 - h_1)}{L}.$$

The groundwater regime in the Rainy Creek Complex was evaluated from observation, collection of well data and the performance of tests in shallow and deep holes drilled during the summer of 1981. For the purposes of the study the complex was broken into five sections : Study Area 1,

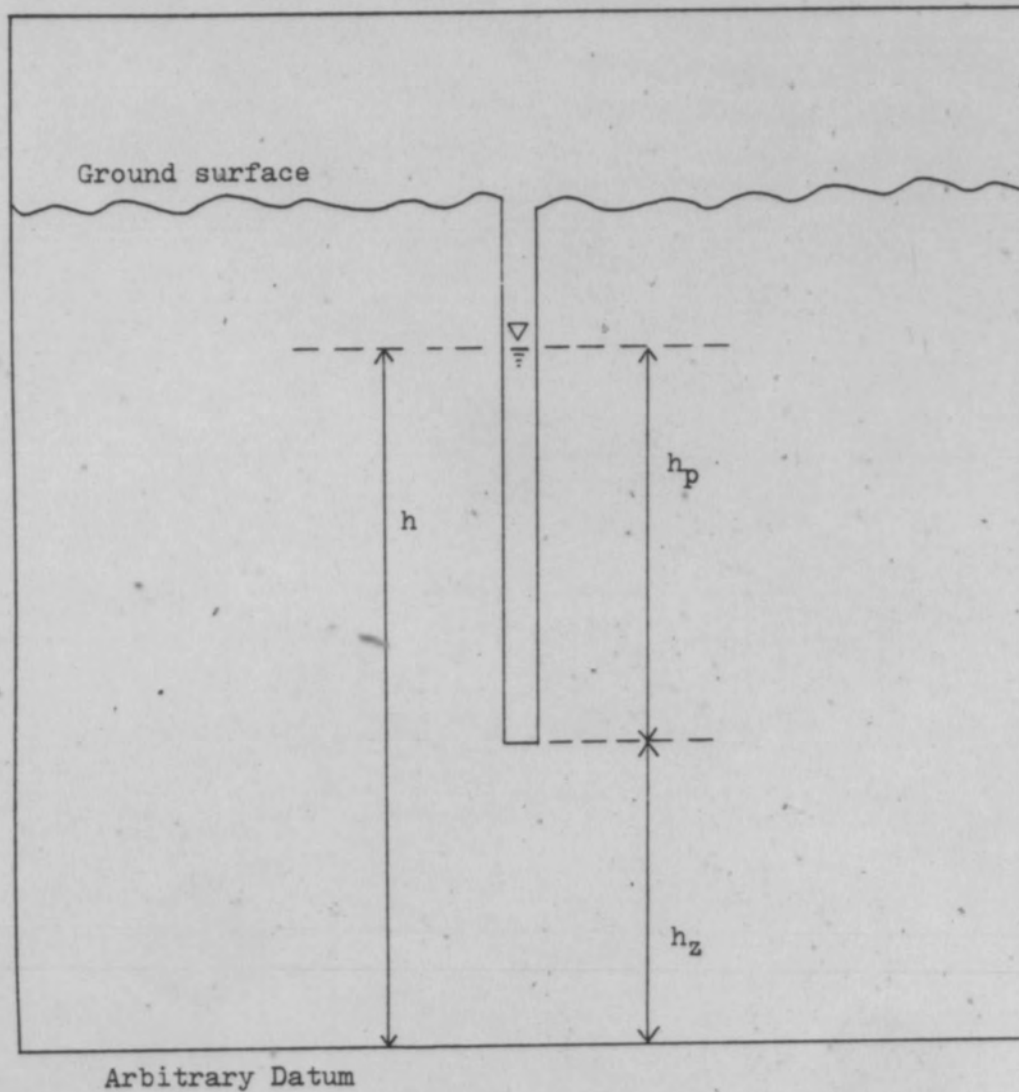


Figure 6. Hydraulic head h , pressure head h_p , and elevation head h_z .

Study Area 2, Study Area 3, the deep holes, and the upper Carney Creek Area.

Study Area 1

Study Area 1 is situated in the south-south-eastern part of the mine in the "vermiculite" pyroxenite and magnetite pyroxenite bodies (Figure 7). The topography slopes approximately twelve degrees to the south in the northern section and from there gradually slopes in a westerly direction at approximately fifteen degrees. Borings used for the study were made on four development drilling roads with alternating roads having one-hundred and two-hundred foot spacings. Thirty-nine holes were used with depth of boring not exceeding 175 feet. Figures 8 through 11 show the subsurface static water levels, depth of water encountered while drilling, and the overburden, vermiculite pyroxenite, and the biotite pyroxenite bodies.

Most of the water encountered in Study Area 1 was found in the north central section. The topography in this section slopes from a westerly direction to a southerly one and forms a broad depression. Recharge to the area is mainly by infiltration from precipitation. Discharge is by subsurface and overland flow to Carney Creek. The northwest section of the area had considerably less water than the northern central portion and the southern section had little or none.

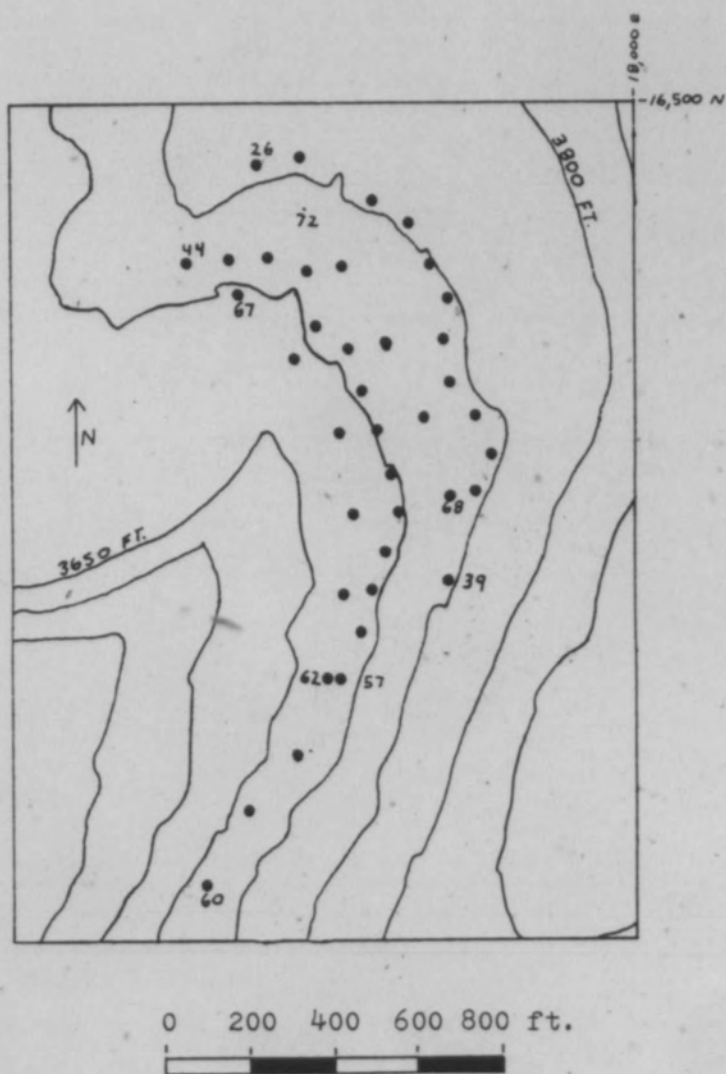
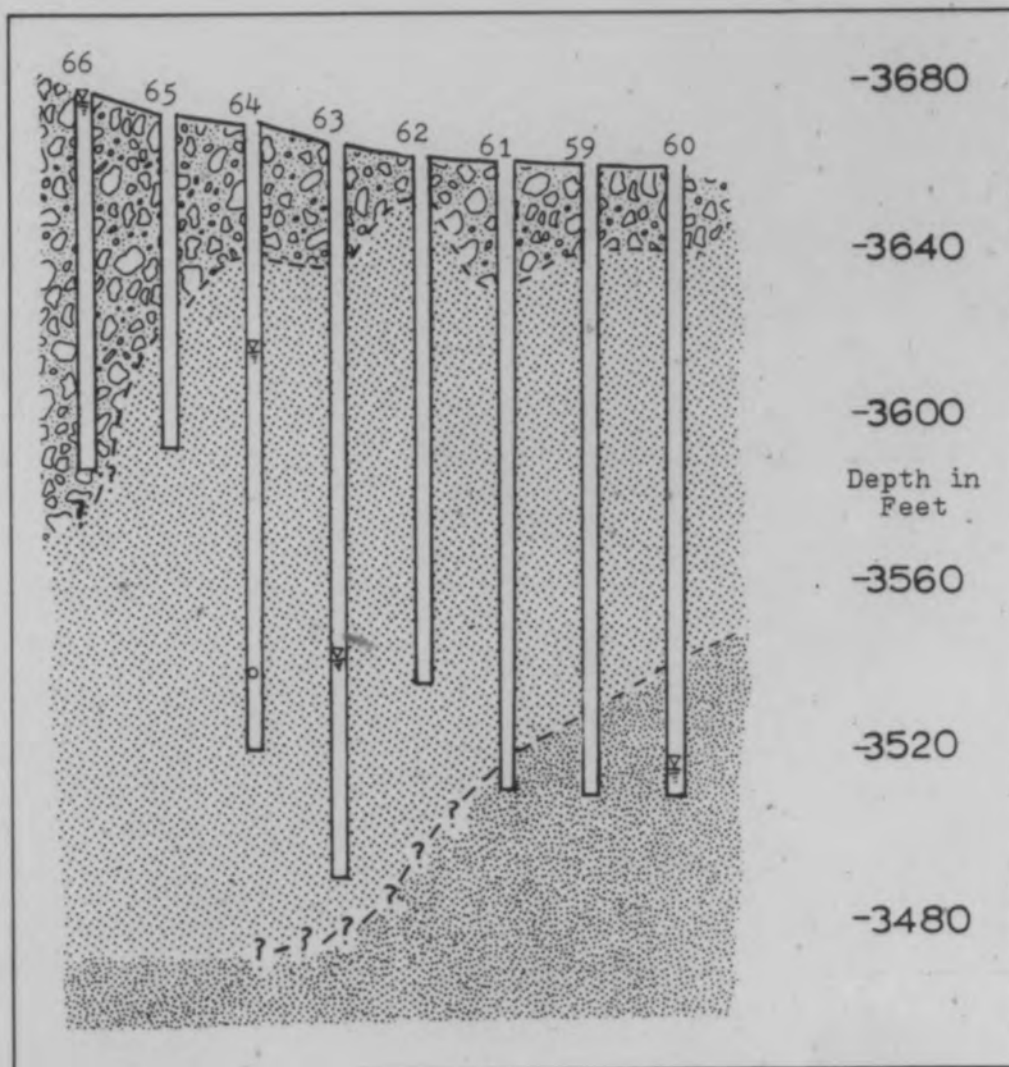


Figure 7. Study Area 1, borehole location map.








-  Overburden
-  "Vermiculite" pyroxenite
-  Biotite pyroxenite
-  Static water level
-  Initial water level during drilling

Figure 8. Cross-section 1A, showing water level data.

Note: Width of drill holes horizontally exaggerated

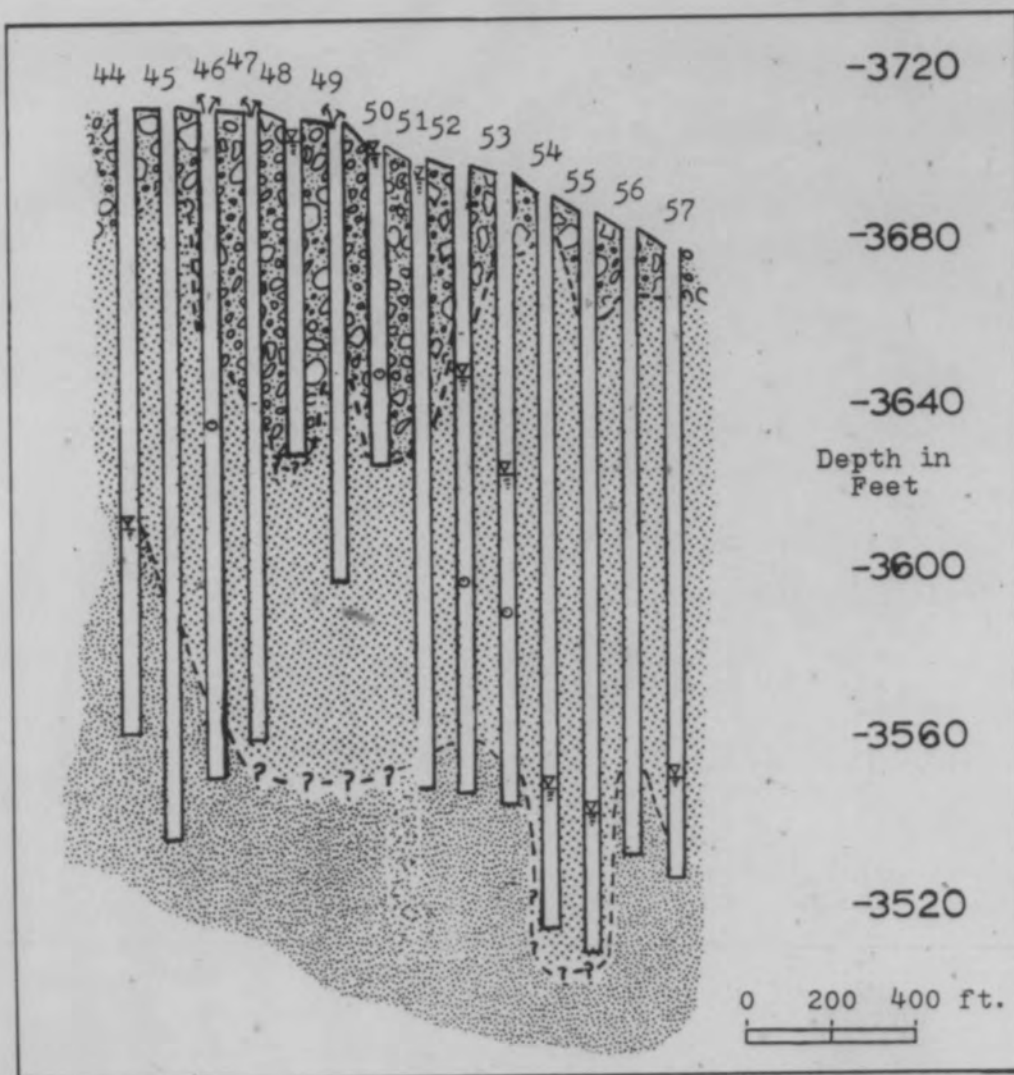


Figure 9. Cross-section 1B, showing water level data. (see Figure 8 for explanation.)

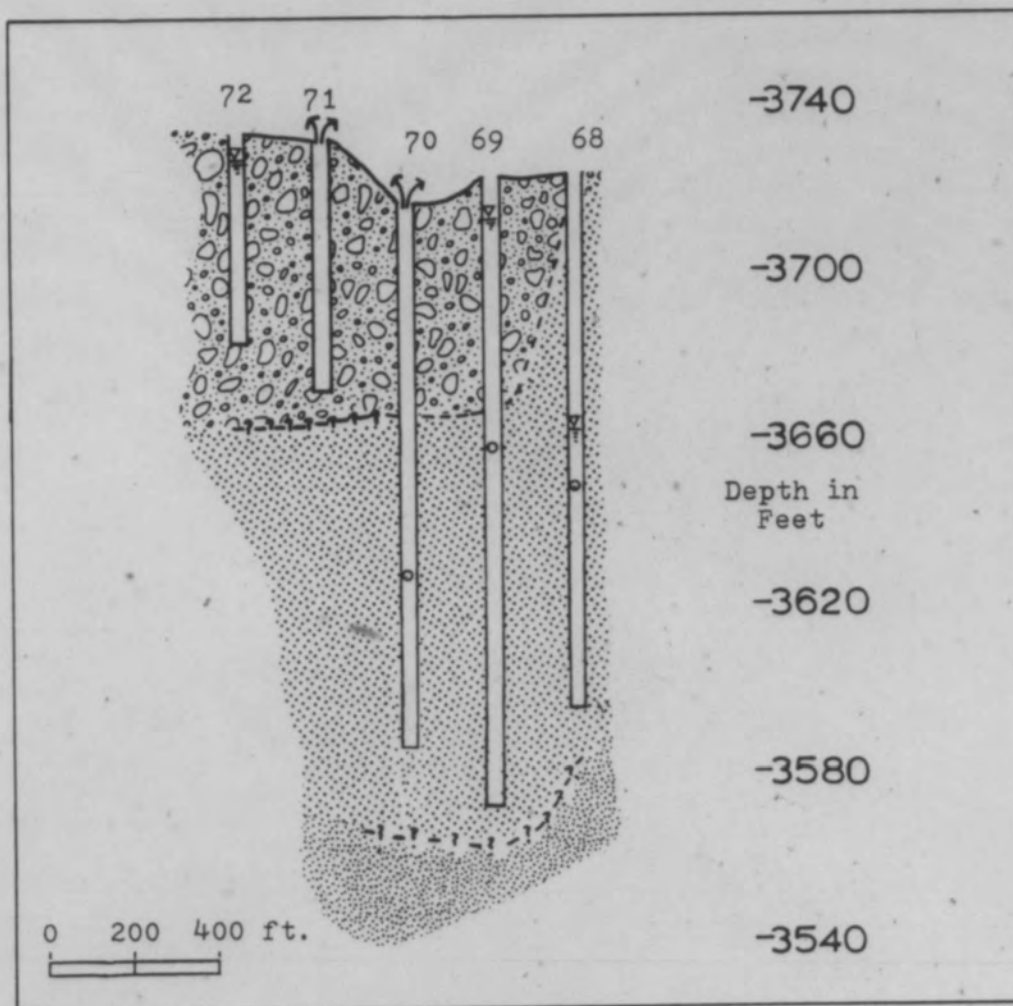


Figure 10. Cross-section 1C, showing water level data. (See Figure 8 for explanation.)

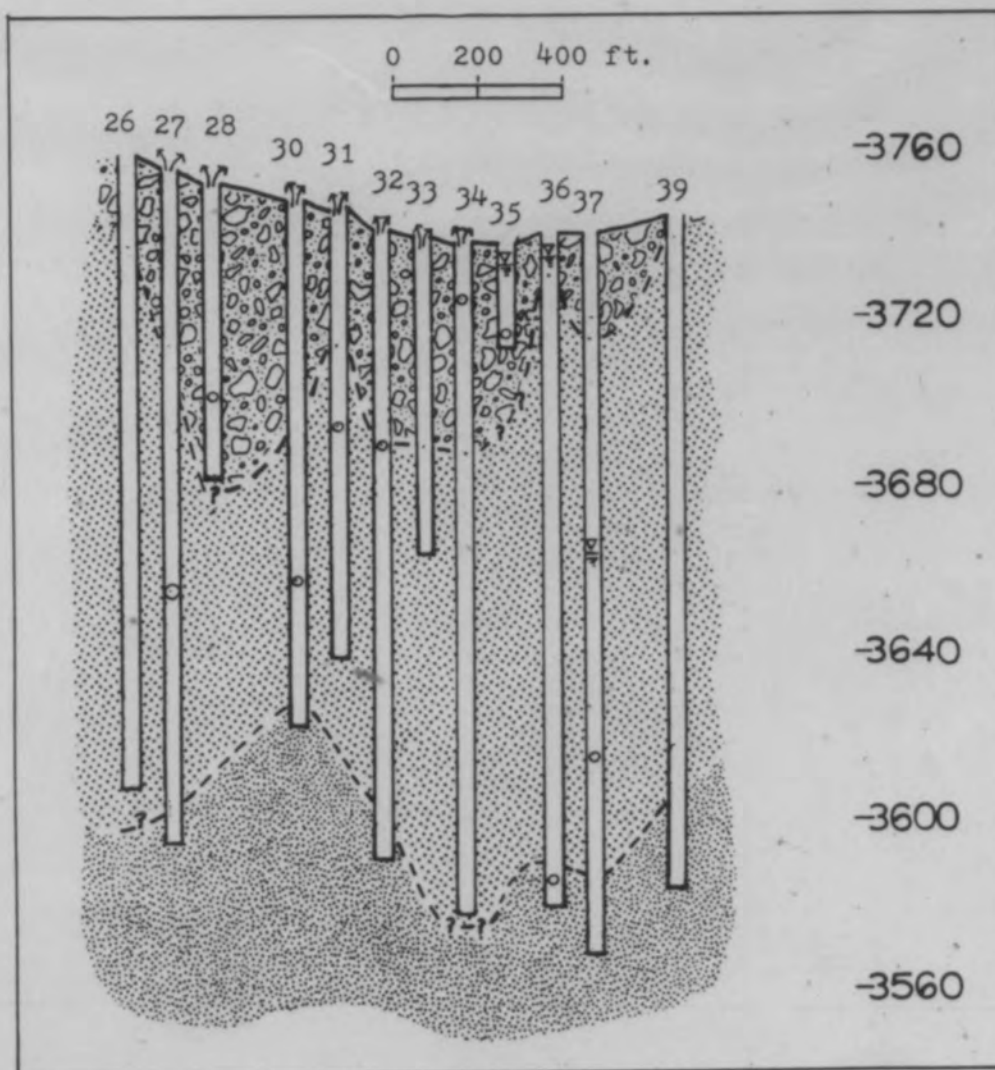
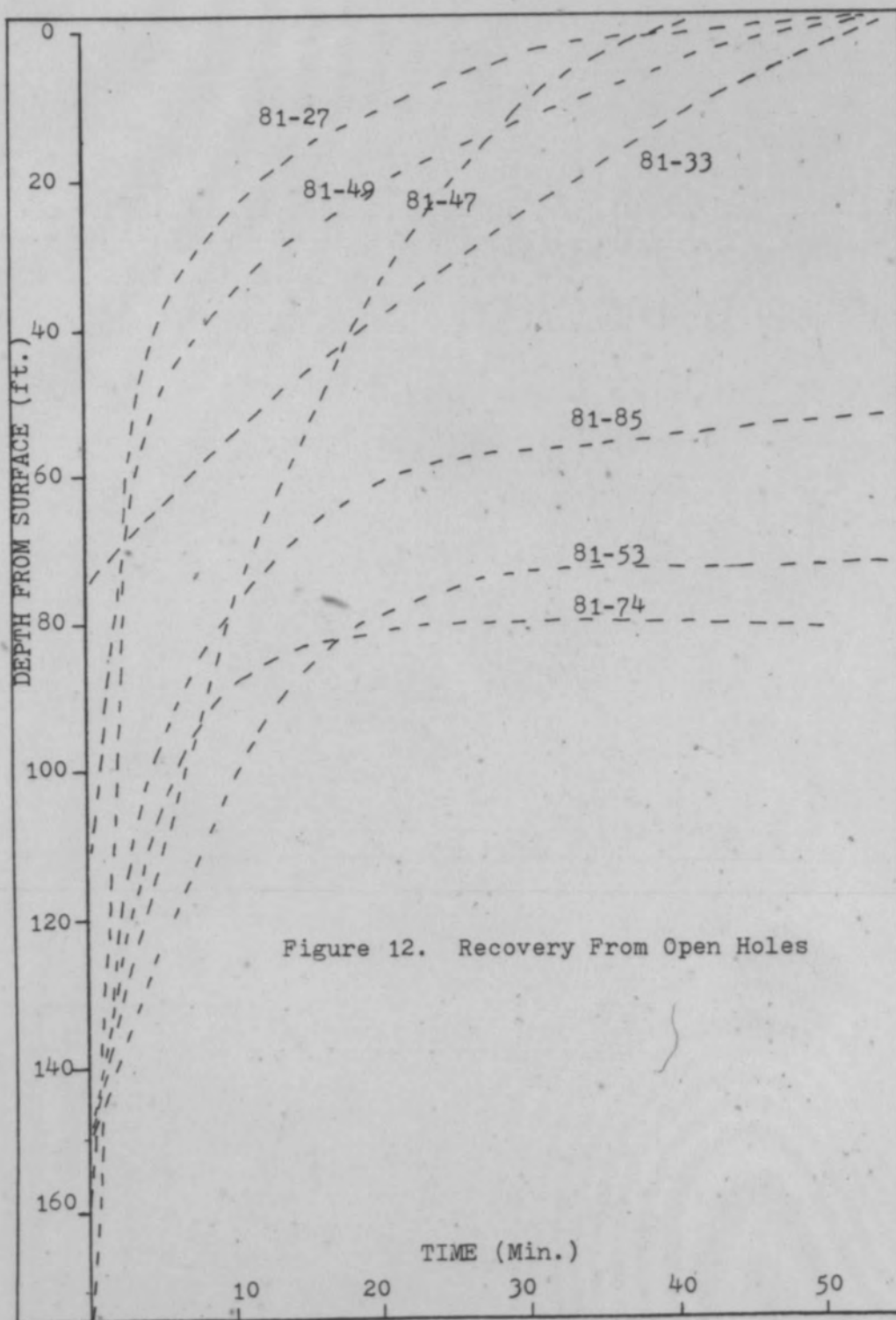


Figure 11. Cross-section 1D, showing water level data. (See Figure 8 for explanation.)

Overburden thickness was also considerably higher in the north central section than in the other areas. Fifty feet of overburden was not uncommon in this area, and a few holes had overburden in excess of 80 feet. The overburden appears to be less permeable than the underlying pyroxenite and forms a semi-confining layer. The overburden thus confines the water beneath and increases the pore water pressure. It is thus concluded by the writer that the groundwater evaluated in Study Area 1 is under piezometric conditions.

Most of the holes drilled in the thick overburden were either under artesian conditions where the hydraulic head was above the land surface or had high static water levels. The water produced by the twelve artesian holes was approximately 1-2 gpm. The holes flowed for months until they either became unstable and collapsed or were covered up by snow and observations were no longer made.

The rise in water levels after the cessation of drilling for some of the holes is shown in Figure 12. It was assumed that the water level was at the bottom of the hole when drilling was stopped. Water levels were measured as soon as possible when all the drill stems were pulled out of the hole. In all these plots the rise in water level was very fast at first and then tapered off. It can be seen from Figure 12 that holes 27, 49, 33 and 47 became artesian within 60 minutes after drilling was stopped.



Also observed in the artesian holes was the release of trapped gases that bubbled up through the groundwater continuously while the holes were open. This observation may in part be due to the high pressure air used during drilling.

No formal permeability tests were conducted in this area.

Study Area 2

Study Area 2 is north of the present mine and just east of the coarse tailings from the milling operations (Figure 13). The topography slopes approximately between 13 and 17 degrees to the north-northwest. Recharge to the area is supplied primarily as subsurface flow from the top of the mountain. Overland flow from a small spring above the area runs near hole 84. Although the volume is unknown water probably infiltrates into the area from the coarse tailings slurry being discharged above. Discharge on this side of the mountain is to Fleetwood Creek as baseflow. Two drilling roads were used, the upper one was drilled at 100 foot spacings and the lower one at 200 foot spacings.

The overburden confining layer was only significant in two places. Figure 14 shows a large amount of overburden between holes 84 to 91. Apparently, this is the result of the hole being drilled in a broad gully (Figure 13).

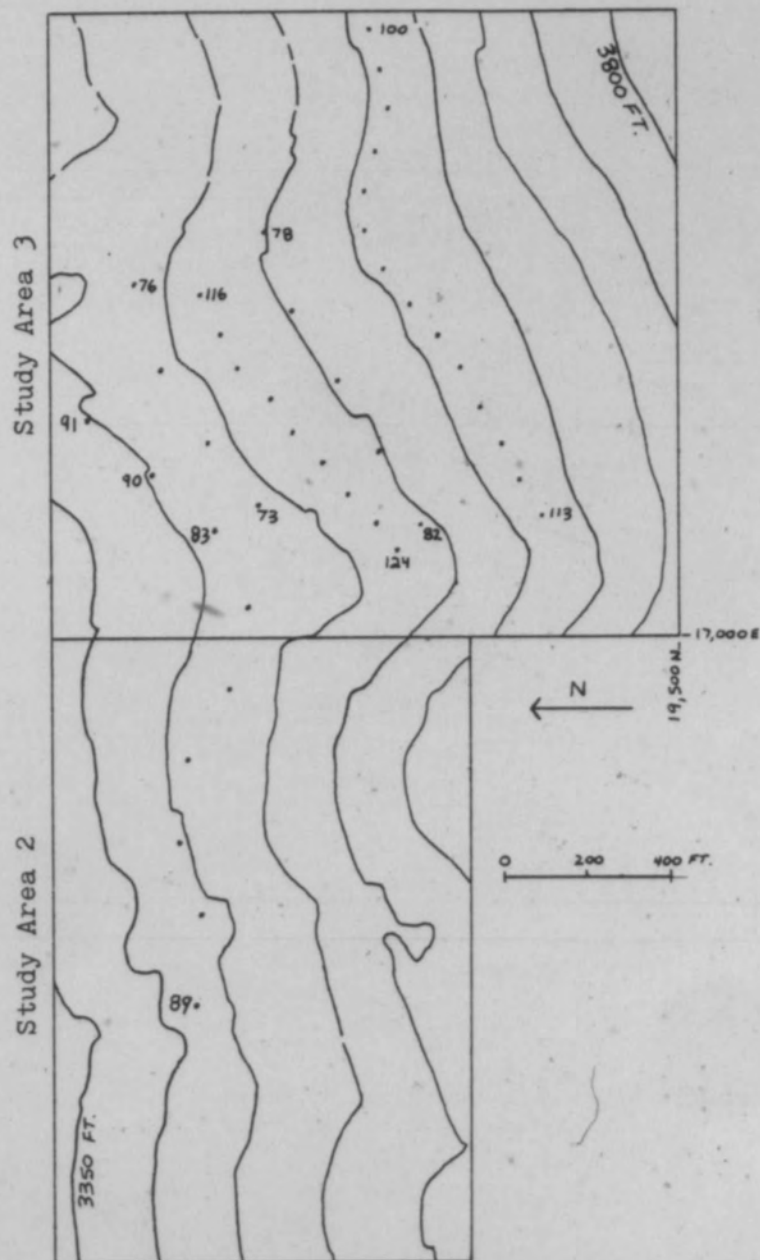


Figure 13. Study area 2 and 3, borehole location map.

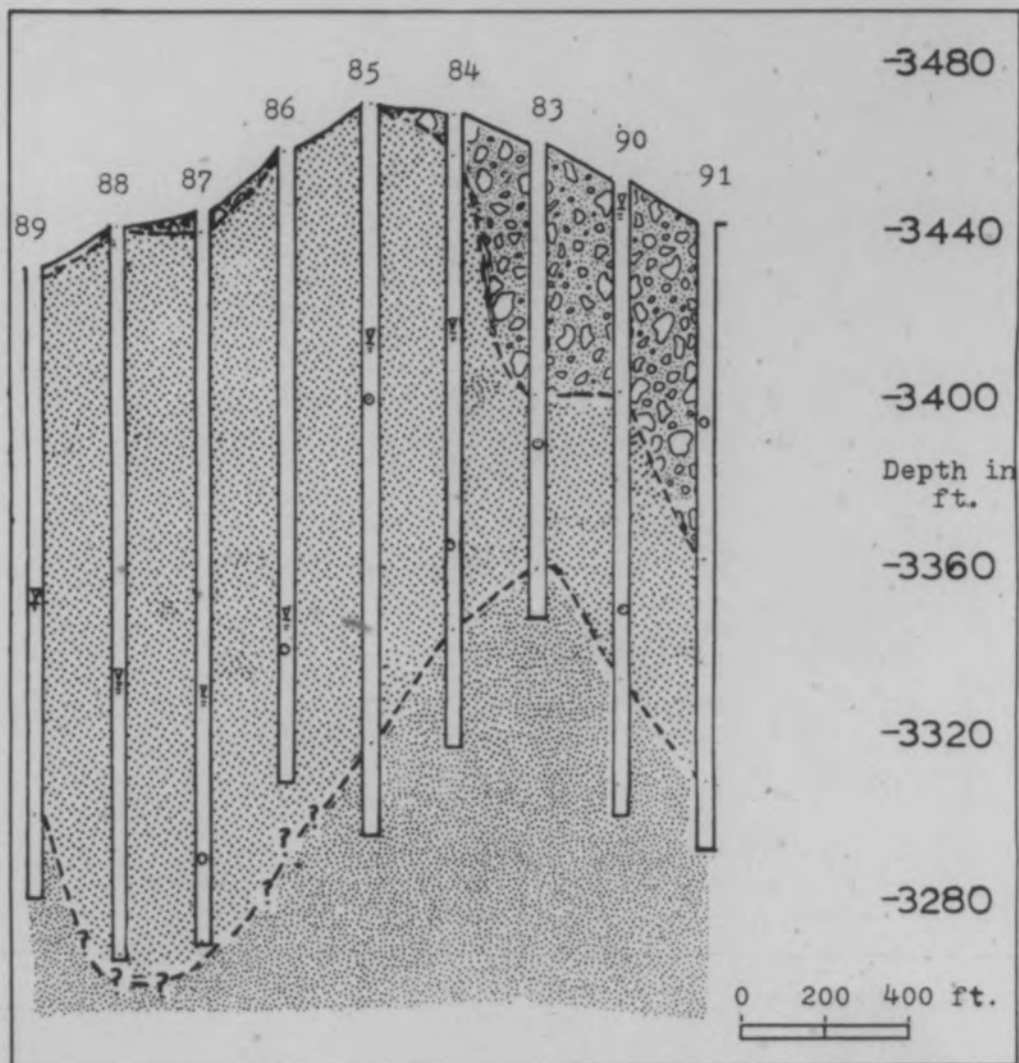


Figure 14. Cross-section 2-A, showing water level data. (See Figure 8 for explanation.)

Like Study Area 1, more water was encountered beneath areas of thick overburden. Correspondingly, the volume of water decreases as the overburden narrows. Holes 83 and 91 do not seem to follow the pattern, although water was encountered in both these holes when drilling. In fact, both these holes produced in excess of 20 gpm while being drilled. This paradox is possibly the result of impervious zones, possibly syenite or tremolite dikes, impeding groundwater flow to the holes.

Water infiltrating from the tailings slurry is evident in the western most holes (Figures 14 and 15). Hole 99 sustained water at shallow depth and produced 40-50 gpm at depth. There is also an increase in the static water level from hole 87 toward the coarse tailings.

Pump Test. A pump test was performed in Study Area 2 to determine the hydraulic properties of the vermiculite pyroxenite. The pump was set at a depth of 123 feet in hole 96. Hole 96 extends into the beginning of the biotite pyroxenite and is thus not strictly contained in the "vermiculite" pyroxenite. Because the biotite pyroxenite near the end of the hole contained three percent or less biotite and because the "vermiculite" in this zone was still of good quality, the writer feels the effect of the biotite pyroxenite is negligible. The 150 foot drill hole was lined with a four inch plastic casing with the bottom ten feet perforated to allow access to groundwater into the

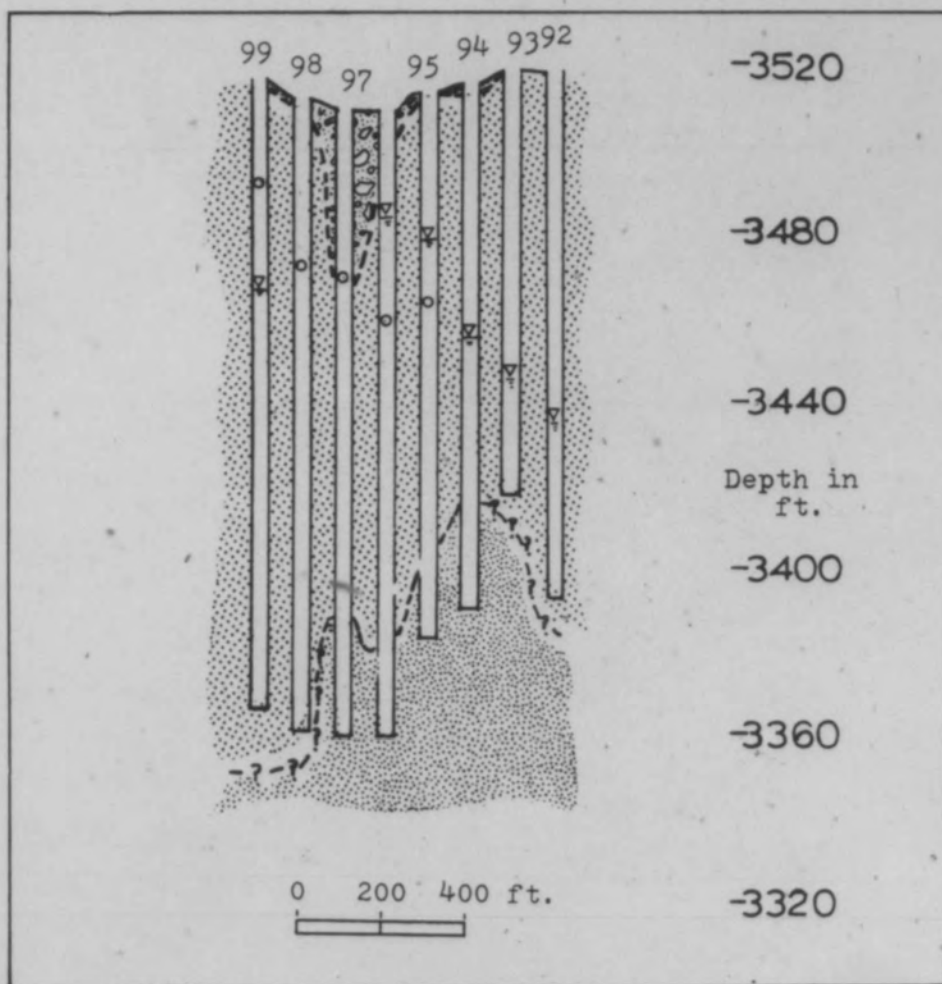


Figure 15. Cross-section 2B, showing water level data. (See Figure 8 for explanation.)

casing. Two one inch observational open standpipes were installed, one at a horizontal distance of 300 feet (hole 99) and depth of 152 feet and one at a distance of 100 feet (hole 95) and a depth of 131 feet. Both observational open standpipes were situated in the same line as the pumping well.

Data from the pumping test were analyzed using the Theis equation (Theis, 1935) and the Theis straight line recovery method (Kruseman, 1967). Hole 96 was pumped at 20 gpm for 13 minutes and achieved a drawdown of 19 feet. There was no drawdown observed in either of the open standpipes when the pump was stopped. Recovery data were taken for 35 minutes after the pump was stopped.

Assumptions and limiting conditions underlying the above equations are the following : (1) that part of the aquifer influenced by the pumping test is homogeneous, isotropic, and of constant thickness ; (2) the aquifer is of infinite areal extent ; (3) before pumping the piezometric surface is horizontal ; (4) the pumped well penetrates and draws water from the entire thickness of the aquifer ; (5) the pumping well has a constant discharge rate ; (6) the diameter of the pumped well is infinitesimal ; (7) the aquifer is confined by an impermeable layer above and below ; (8) water taken from storage is discharged instantaneously with decline in head ; (9) flow to the well is unsteady ; (10) for the Theis straight line recovery method the value of u is small ($< .01$), meaning r is small

and/or t is large.

In practice, the above assumptions and limitations are rarely if ever completely satisfied. But awareness of them and their degree of significance in various regimes is essential to the understanding and usefulness of computed results.

The vermiculite pyroxenite in Study Area 2 is neither homogeneous or isotropic, the pumped well is only perforated ten feet at the bottom, the overburden is not a true confining layer and its thickness varies considerably. Also, because of difficulties with the pump, the pumping time was abnormally short. Therefore, the results obtained from the test are only useful as an approximation of the average conditions at best.

According to Theis (1935), a well pumped for a known period of time and then left to recover will have the same residual drawdown as if the pump was left on and a recharge well was installed at the same point at the instant the pump was turned off. Accordingly the residual drawdown s' at any instant is given by the equation : $s' = \frac{Q}{4\pi T} [W(u) - W(u')]$

$$\text{where } u = \frac{r^2 S}{4Tt} \text{ and } u' = \frac{r^2 S}{4Tt'}$$

and where s' = residual drawdown ;

r = distance from pumping well ;

S = storativity ;

T = transmissivity ;

t' = time since pumping started ;

Q = rate of discharge during pumping ; and

$W(u)$ = well function.

When r is small and/or t' is large the above equation can be written as:

$$s' = \frac{2.30Q}{4\pi T} \cdot \log t/t' .$$

This is known as the Theis recovery equation. Figure 16 shows the semi-logarithmic plot of the recovery data from the pumping test. According to the above equation a plot of s' vs. $\log t/t'$ should theoretically form a straight line and intersect the origin. The points plotted from the recovery data form a line that passes below the origin. Theis (1935) explains that the line probably passes below the origin because the water table rises faster than the medium can be saturated. The slope of the line $\frac{s'}{\log t/t'}$ equals $\frac{2.30}{4\pi T}$ so that s' the residual drawdown per log cycle

can be substituted into the equation:

$$T = \frac{2.30}{4\pi \Delta s'} .$$

The transmissivity computed from the graph is $.4 \text{ cm}^2/\text{sec}$. Using an aquifer thickness of 32.61 m a value of 1.2×10^{-4} cm/s was computed for the hydraulic conductivity. This value is reasonable in that the "vermiculite" pyroxenite behaves like a semi-consolidated sandstone. According to Freeze and Cherry (1979) this value for the hydraulic conductivity falls well within the range for fractured igneous and metamorphic rocks and also corresponds to a dirty sand in unconsolidated deposits. The assumption that u was less

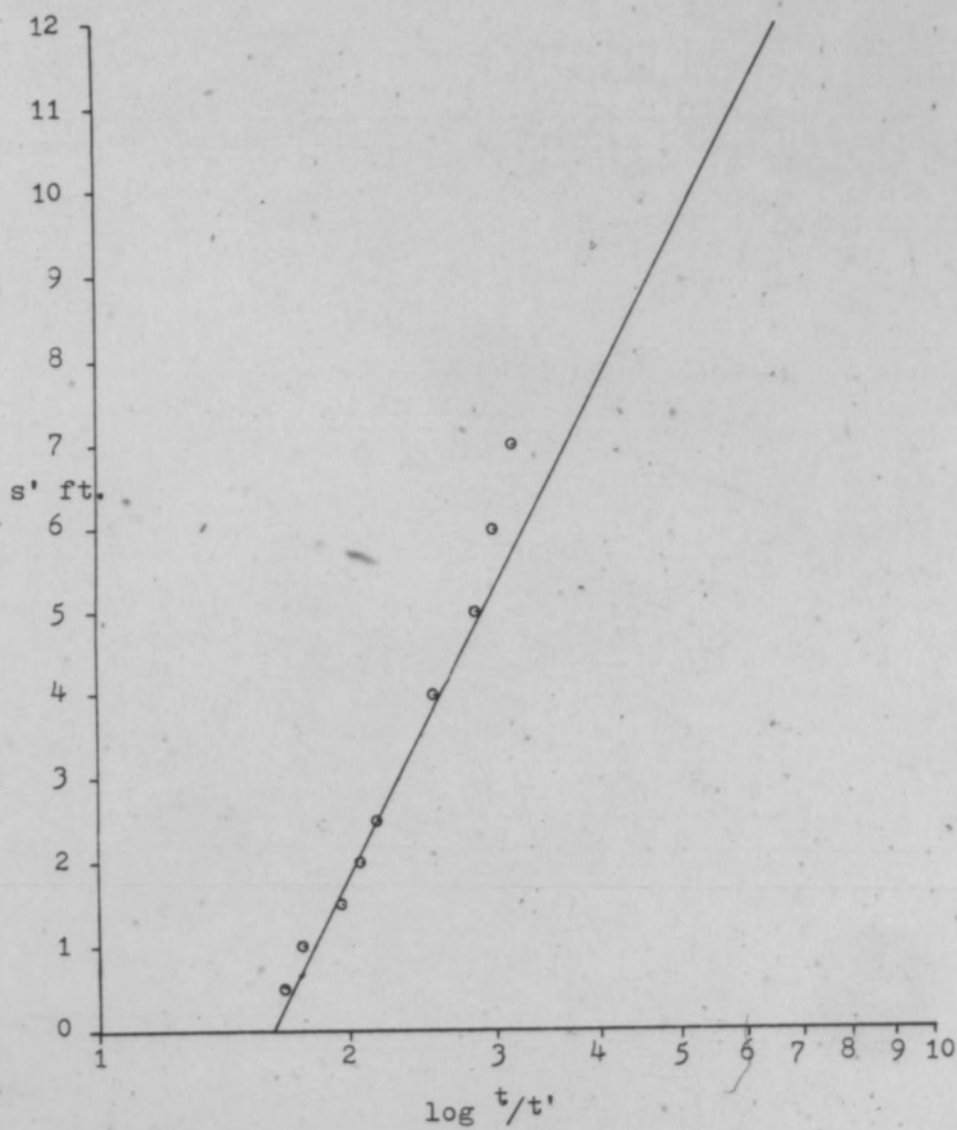


Figure 16. Semi-logarithmic plot of Recovery data from pump test.

than .01 when using the Theis straight line recovery method was not achieved, but McWhorter (1977) states a value $< .1$ (.06 calculated here) is accurate within 6%.

Study Area 3

Study Area 3 is north of the mine area and east-south-east of Study Area 2 (Figure 13). The topography in the area slopes to the northwest approximately twelve degrees, gradually steepening toward the mountain. Two broad gullies border the study area, one on the southwest side and one on the northeast side ; the one on the southwest is more prominent. No surface water flows in either of the gullies. Groundwater flows in Study Area 2 from the top of the mountain to Fleetwood Creek. The small spring in Study Area Number 2 discharges in the southwest gully near the main access road.

There were four roads drilled in this area with alternating roads having 100 and 200 foot drill spacings. Figures 17 to 20 show the groundwater and subsurface geologic conditions in the area. Except for drill hole 76, static water levels generally increased from northeast to southwest toward the deeper of the two gullies. Overburden was thicker toward the middle of the sections. It is apparent from the section that the overburden did not rigidly correlate with the highest static water levels as did the first two study areas.

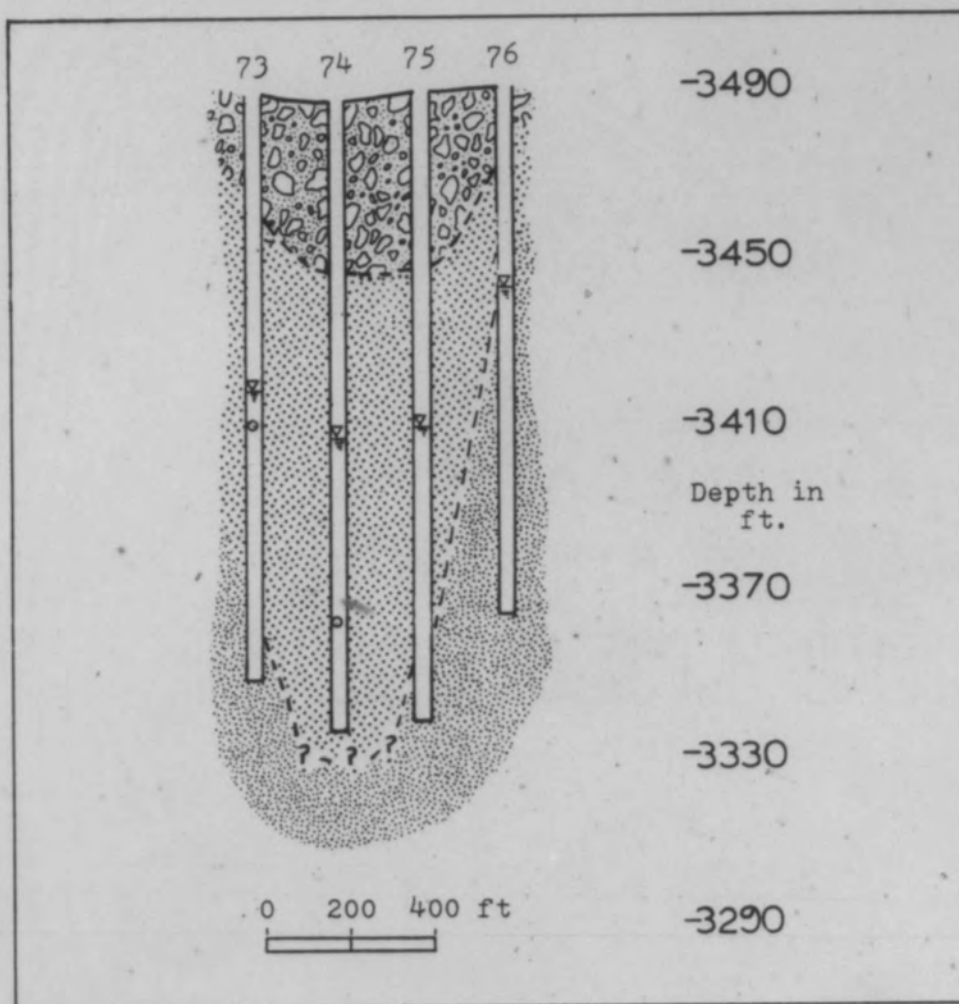


Figure 17. Cross-section 3-A, showing water level data. (See Figure 8 for explanation.)

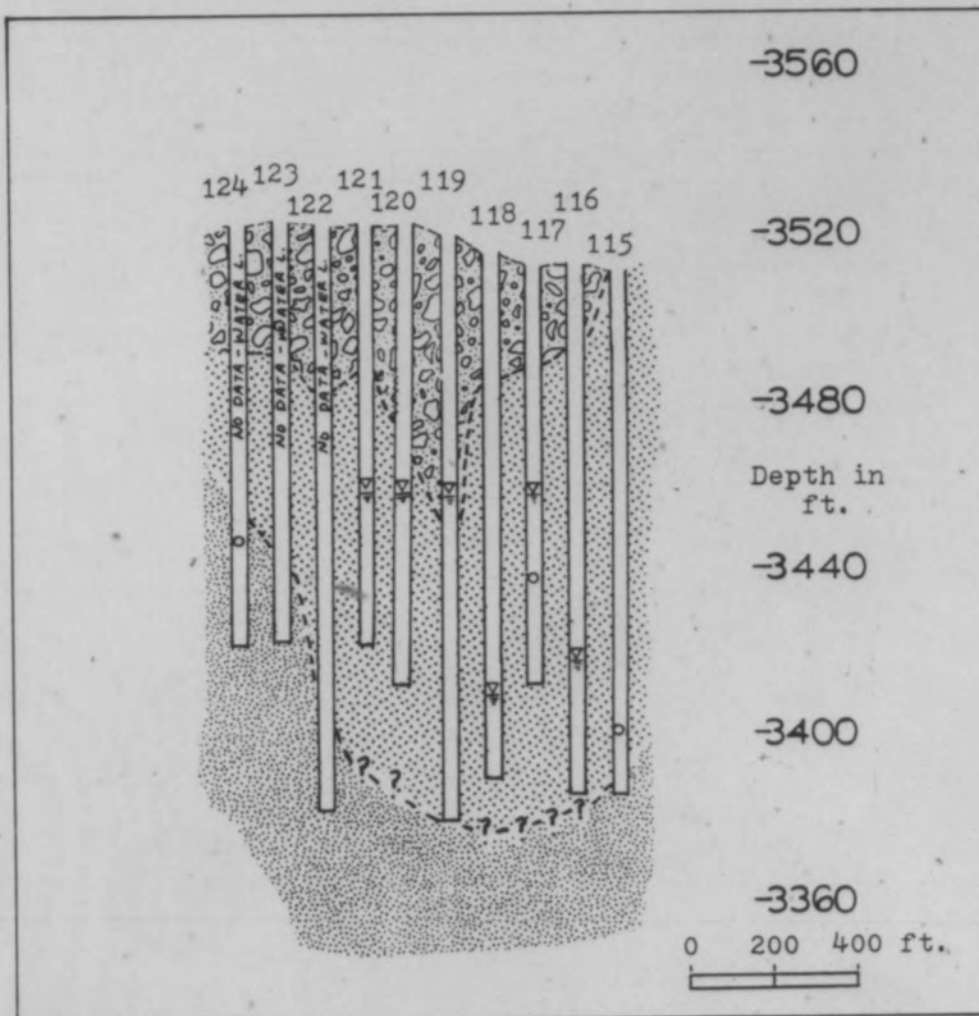


Figure 18. Cross-section 3-B, showing water level data. (See Figure 8 for explanation.)

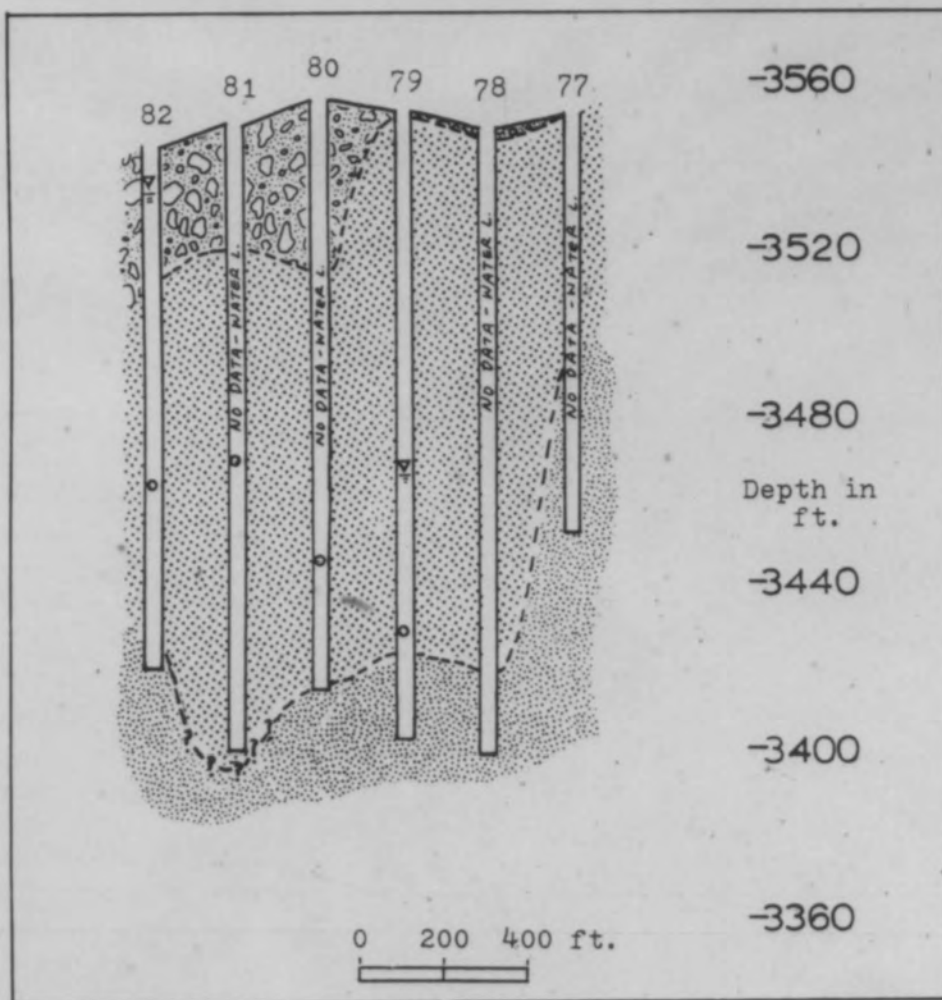


Figure 19. Cross-section 3-C, showing water level data. (See Figure 8 for explanation.)

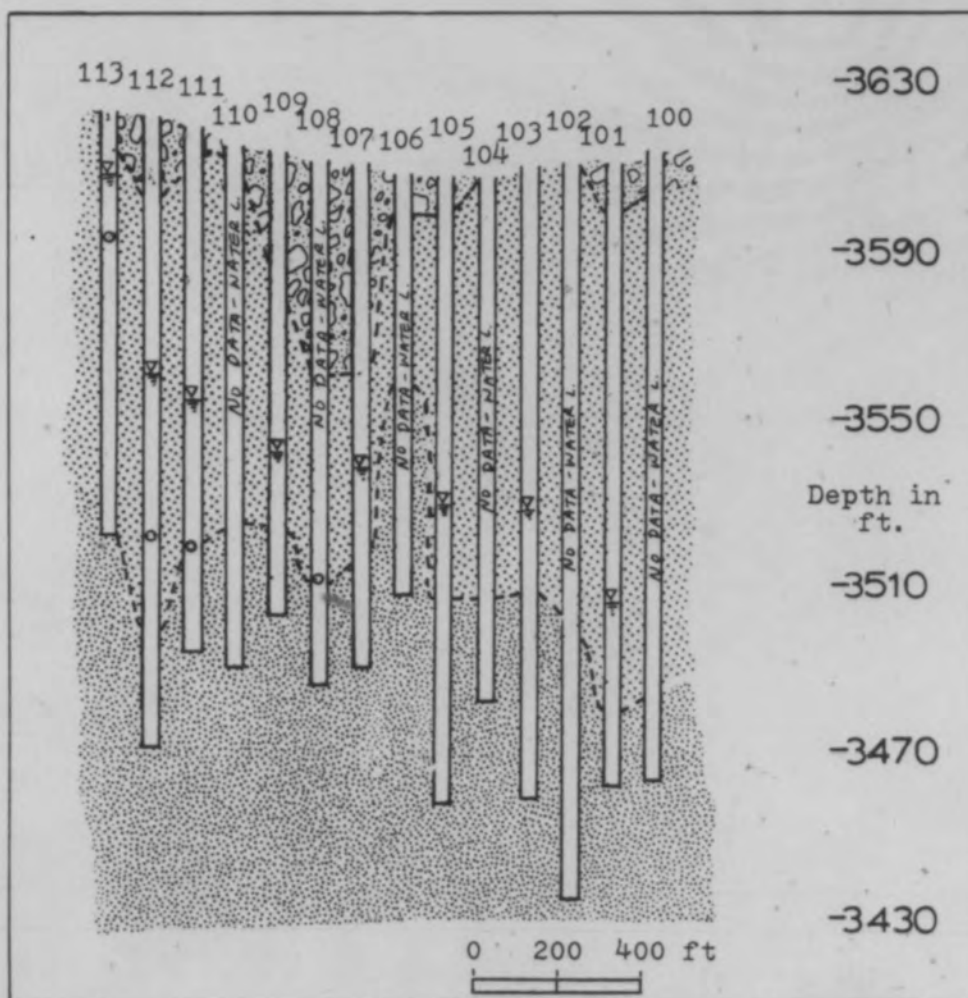


Figure 20. Cross-section 3-D, showing water level data. (See Figure 8 for explanation.)

Slug Test. A slug test was performed in the open standpipe installed in hole 74. In contrast to a pump test where the hydraulic conductivity is evaluated over large lateral distances, the slug test only samples the medium in the immediate vicinity of the hole. The values from a slug test are therefore not as representative of the medium as are those from a pump test. The slug test does have the advantage in that it is relatively cheap and is easier to perform than the pump test.

The open standpipe in hole 74 is 137 feet deep with the bottom 10 feet perforated with 1/4 and 1/8 inch holes. The hole was backfilled with drill cuttings and bentonite was poured around the outside of the standpipe above the perforated zone to prevent water from entering the hole from the surface. A 1200 gallon water truck was used as the source of water for the test.

The equilibrium condition in the open standpipe was changed by introducing a steady flow of water. The hydraulic head was increased in the standpipe until it reached the ground surface (the bottom of the piezometer is used as the datum point) where it was held for approximately one minute before the test was begun. The inflow from the water truck was stopped and the decrease in the hydraulic head versus time was measured. Water level measurements were taken at 15 second intervals for the first five minutes and 45 seconds,

one minute intervals for the next 26 minutes, two minute intervals for the next four minutes, and five minute intervals for the last 30 minutes, respectively.

Two large surges occurred during the slug test. The first one occurred after the head fell 40.5 feet at which time about two minutes had elapsed in the test. During the surge the head increased 11.5 feet in less than 30 seconds, leveled off and then began lowering again. The second surge occurred seven minutes, 22 seconds after the first one, when the water level was 68 feet below the surface. The head increased 23 feet to a level 45 feet below the surface in approximately three minutes. After the second surge the hydraulic head steadily decreased until the water level was 77 feet 3 inches below the surface in 45 minutes after the start of the test. At this time the test was stopped.

The reason for the two surges is not entirely clear to the writer. Bubbling groundwater was observed in drill holes for months suggesting a high gas content in the pyroxenite. It is hard to tell what quantity was insitu gas as compared to that derived from drilling. Freeze and Cherry (1979) give three means by which gas is dissolved in groundwater: (1) exposure of surface and rain water to the earth's atmosphere before infiltration takes place; (2) exposure to soil gases during infiltration; and (3) chemical or

biochemical gas production in the saturated zone involving reactions with groundwater, minerals, organic matter, and bacterial activity. The writer feels these gases, of unknown composition, were linked with the surges observed during the test.

Raising the hydrostatic head almost 80 feet may have been responsible for initiating the dynamic effects observed in the system. An increased head in the standpipe would have increased the pore water pressure in the surrounding zone. The increase in water pressure would cause the volume of gas in solution to decrease with an accompanying deficiency of water flowing into the standpipe (Hvorslev, 1951). When this pressure was lowered as the hydrostatic head decreased, a rapid expansion of gas in the pyroxenite would have forced water back into the standpipe causing a water level increase. Thus, the head was high enough once more to cause a pore water pressure increase resulting in a second surge. This cyclic-like effect would only be seen if sufficient gas were available in the system.

The high hydrostatic head may have had additional effects on the system. Gases occupying pore spaces within the pyroxenite may have been physically forced into the formation and released upon lowering of the head (Bryson Trexler, Kennecott Minerals, oral communication). This may have also contributed to the cyclic effect produced during the test.

Gas could have been produced if warmer water was used for the slug test. The warmer water reacting with colder groundwater may have caused certain gases to come out of solution or expand the trapped gases in pore spaces. The combined effect would have produced air bubbles in the standpipe, possibly causing the surging effect observed during the test. Without identification of the gases and the temperatures of the waters involved it is hard to say for sure if this was the case. Considering that the test was done in the late evening (8:49 p. m. - 9:55 p. m.), with the air temperature rather cool, the writer does not feel the temperature difference was great enough for this to be possible.

Hydraulic Conductivity from the Slug Test. The formula used for determining the hydraulic conductivity from a slug test is given in Hvorslev (1951). The formula is given by:

$$K_h = \frac{d^2 \cdot \log_e \frac{2ML}{D} \log_e H_1/H_2}{8 \cdot L \cdot (t_2 - t_1)}$$

where: K_h = horizontal hydraulic conductivity

M = transformation ratio

L = length, intake

d = diameter, standpipe

D = diameter, intake

H = head

t = time (see Figure 21)

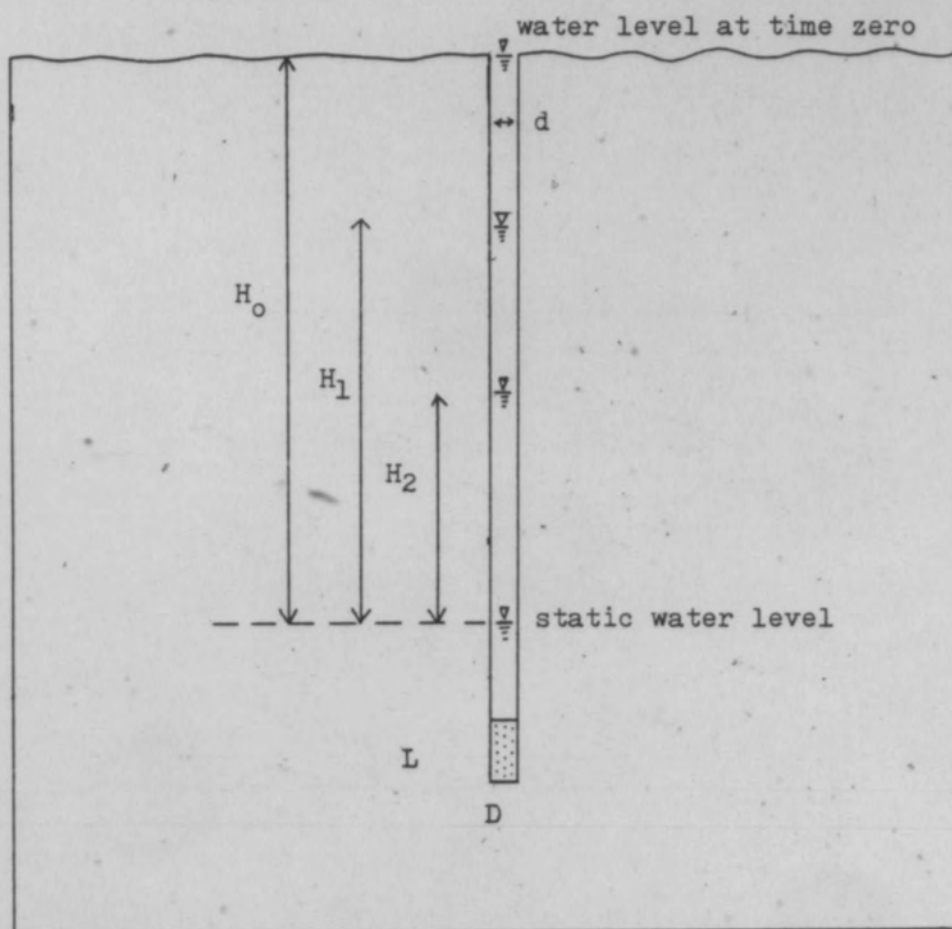


Figure 21. Falling head field test - Slug test.

for a well - point filter in uniform soil for $\frac{ML}{D} > 4$. The terms in the equation for the shape factor are:

$$\frac{2\pi L}{\log_e (2L/D)} .$$

From a plot of H/H_0 versus t a straight line is drawn through the origin and two points are chosen on the line to calculate the hydraulic conductivity.

Drawing a straight line through the points obtained from the slug test was impossible because of the deviations caused by the two surges (Figure 22). Because of this predicament, the surges were graphically removed in hopes of obtaining a straight line as seen in Figure 23. It was possible to draw a line through these points and the hydraulic conductivity calculated was determined to be 2.0×10^{-3} cm/s. For comparison the hydraulic conductivity was also determined using the points before the first surge occurred and those points after the second surge (Figure 22). Hydraulic conductivities of 7.0×10^{-3} cm/s and 1.2×10^{-3} cm/s were calculated from these lines, respectively.

The validity of the hydraulic conductivity is questionable because of the surges and the method used in obtaining a straight line. Reassuring to the writer was the fact that the slopes of the lines during recovery in Figure 22 were reasonably constant and the value obtained was within an order of magnitude of that calculated from the pump test. Also, taking into consideration that the open standpipe was installed in a six inch drill hole and back-

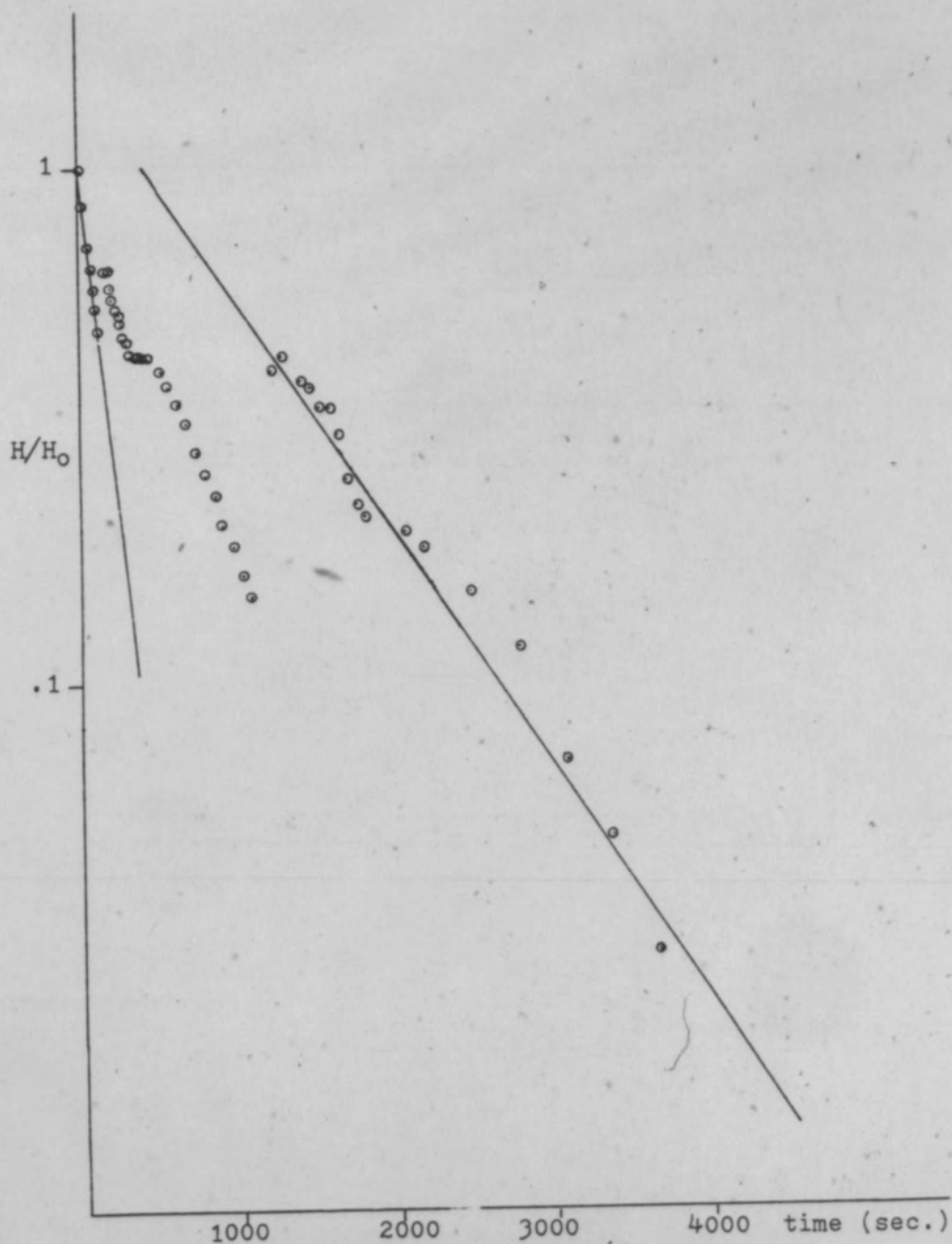


Figure 22. Semi-Log. plot of H/H_0 versus time for slug test.

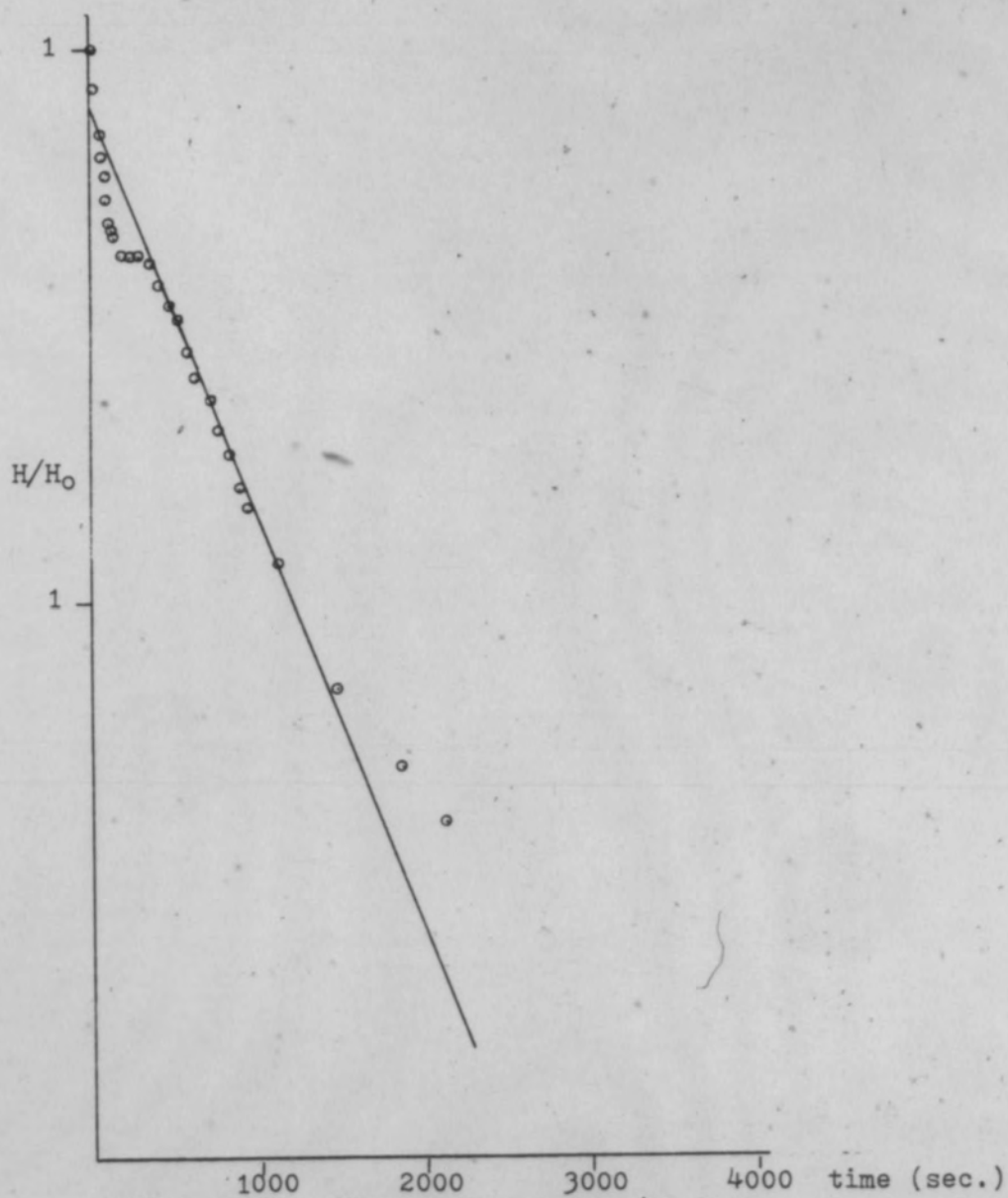


Figure 23. Semi-log.plot of H/H_0 vs. time after surges removed.

filled with drill cuttings, the value seems quite reasonable.

Deep Holes

Two deep holes were drilled in the mine area. Hole 130 is located on the 22nd mining level and was drilled to a depth of 900 feet. The second hole, 131, was drilled north of the present working area to a depth of 970 feet. These holes were drilled to evaluate "vermiculite" quality at depth and to locate and quantify base and precious metal concentrations. The writer did not supervise the drilling of the deep holes and groundwater data were collected by mine personnel.

The first 10 feet of hole 130 consisted of overburden, the next 15 feet was "vermiculite" pyroxenite, and the rest of the 900 foot hole was biotite pyroxenite. Trace quantities of good quality "vermiculite" were consistently found in the deep hole. The genesis of this small quantity of "vermiculite" will be discussed in the section entitled "Present Studies of "Vermiculite" in the last section of the thesis.

No water was encountered while drilling the hole until about the 225 foot level was reached. There, a small seep like zone produced about 1 gpm. By 500 feet the hole discharged approximately 25 gpm. At 700 feet the hole produced between 350 and 500 gpm which marked a significant

increase over the 200 foot span. Drilling was stopped at 900 feet and by this depth 1000-1200 gpm were being discharged to the surface. When visited in January by the writer the static water level was at a depth of 66 feet, indicating the water level was under piezometric conditions.

Hole 130 was not the first deep hole drilled in this area. In 1973 a hole was drilled approximately 200 feet east of Hole 130 on mining level 21. No groundwater data exist for this hole but it has been under artesian conditions since being drilled. A valve mounted cap has been installed on the surface casing. The hole presently discharges about five gpm. A pressure versus discharge test was attempted on the capped hole but was not carried out because of the low water pressure observed when the valve was closed which was caused by a poor connection between the cap assembly and the surface casing.

Hole 131 was drilled north of the working mine area to a depth of 970 feet. No overburden was encountered at the surface; the hole was drilled entirely in the magnetite pyroxenite. This hole is apparently located just over the magnetite pyroxenite-"vermiculite" pyroxenite contact.

Hole 131 did not encounter strong water producing zones as did hole 130. Between 100 feet and 150 feet only a trace of water was found. At 500 feet 25 gpm was being discharged. This 25 gpm flow rate was relatively constant to the end of the hole.

Carney Creek

The Carney Creek Drainage system is located along the southwest border of the mine. Carney Creek rises at 4600 feet and flows northwest where it drains into the central portion of Rainy Creek. Because of the mine waste dumps along the northeast slope and the potential for their expansion the Carney Creek Drainage system has received considerable engineering interest.

The load created by the waste dumps and their impedance of water flow has created instability in the surrounding slopes and in the valley bottom. There is no present indication that the dumps have activated the high angle reverse fault striking through Carney Creek.

The waste dumps are impermeable enough to block the natural flow of surface and subsurface water. The blockage from the dumps has increased the pressure head in the till. Slope failure and heaving of the valley bottom are attributed to hydrostatic uplift and loss of strength in the till (Harding-Lawson Associates, 1974).

Open holes drilled in the area have revealed artesian conditions that produced 5-10 gpm. One of these holes visited during the month of August by the writer was producing 1-2 gpm. Harding-Lawson (1974) believes the aquifer is probably the result of a permeable zone of sandy and gravelly till overlain by a less pervious till. The

artesian conditions are thereby the result of the upper inclination of glacial deposit to the canyon head where recharge takes place.

Conclusions - Groundwater

More than 100 shallow holes (less than 200 feet) and two deep holes (900-1000 feet) were drilled during the study period. The majority of shallow holes were drilled in altered "vermiculite" pyroxenite down to biotite pyroxenite, and magnetite pyroxenite zones.

At one time "vermiculite" pyroxenite and biotite pyroxenite were probably one in the same. Alteration of the upper 100-200 feet has resulted in two zones that are different both mineralogically and from a groundwater standpoint.

Therefore, two distinct aquifers exist within the inner two pyroxenites. The first is the surface blanket of altered vermiculite pyroxenite and the second is the unaltered biotite pyroxenite below the alteration zone.

The vermiculite pyroxenite zone is composed of semi-consolidated soil like rock cut by dikes and veins. The vermiculite pyroxenite appears to have high porosity and is similar to sand. The rock is very easily crushed in the hand. It is plutonic and contains no oriented cleavage, bedding planes, foliation, or the like that could control the direction of groundwater movement.

The hydraulic conductivity and transmissivity, calculated from the pump test, are 1.2×10^{-4} cm/sec and .4 cm²/sec, respectively. The hydraulic conductivity calculated from the slug test was 2.0×10^{-3} cm/sec. For reasons stated earlier, these values can only be used as approximations.

The secondary hydraulic conductivity produced in the "vermiculite" pyroxenite was most likely caused by the swelling and shrinking of the platy minerals and the subsequent leaching of minerals from groundwater circulation.

Holes drilled in this altered zone produced up to 50 gpm. Most of the holes encountering water produced between 10 and 25 gpm. The zone is thus capable of producing and storing a reasonable amount of water.

The biotite pyroxenite is the unaltered rock found below the altered zone. The biotite pyroxenite is more consolidated and less porous than the "vermiculite" pyroxenite above it. Hydraulic conductivity of the biotite pyroxenite was not calculated but appears to be rather low. It is the authors opinion that the hydraulic conductivity undoubtedly increases in areas where pyroxene content is high and the biotite content is correspondingly low. Shear zones, fractures, and joints in the hard biotite pyroxenite are responsible for the substantial water bearing zones. As was discussed in the last section, hole 130 produced 1200 gpm with no reduction observed when drilling was ceased.

Groundwater does appear to be structurally controlled by impervious syenite dikes. Most are high angle and do appear to partition areas. It is commonplace to encounter higher volumes of water after drilling through these dikes. This phenomenon was clearly seen in the "vermiculite" pyroxenite which permits the migration of water more freely (excluding fracture or shear systems) than in the biotite pyroxenite. More holes will have to be drilled in the less permeable biotite pyroxenite before the influence on that medium can be determined. The low volume of water produced in the deep hole 131 may possibly have been caused by syenite dikes impeding flow in that area.

In contrast to the syenite dikes blocking the flow of groundwater other dikes or veins may act as low to medium permeability flow conduits. The numerous quartz veins in the area may be fractured enough to allow groundwater flow. The water-conducting veins would not be nearly as significant as that of the shear zones.

Except where mining has removed the surface material, an overburden layer consisting of reworked glacial deposits and organic material blankets most of the area. Although not as evident in Study Area 3, higher static water levels and a higher volume of water were produced by holes where the overburden layer was thick. The overburden is less permeable than the "vermiculite" pyroxenite and acts as a semi-confining layer holding groundwater under semi-confined

conditions. The upper portion of the overburden contains tree and shrub roots which impede overland flow and facilitate infiltration of surface water.

Confined like conditions can also be produced by a permeability change within the altered "vermiculite" pyroxenite. Permeability may be higher in the weathering front where microfracturing is probably the initial physical effect of alteration from biotite to "vermiculite".

Ground and Surface Water Chemistry

Ground and surface water samples were collected at various locations in the mine area and Rainy Creek. The parameters and trace metal analyses are listed in Table 3. See Figure 24 for a location map of samples 1 through 7. Locations 4 and 7 indicate the water is hard to very hard. The degree of hardness in water is based upon the classification listed below : (Todd, 1976)

Hardness, mg/l as CaCO_3	Water Class
0 - 75	Soft
75 - 150	Moderately Hard
150 - 300	Hard
over 300	Very Hard

Total dissolved solids were significant at some locations but were still well within recommended drinking limits. The sample taken at the mouth of Carney Creek had the highest with 410 mg/l. Elevated turbidity from surface water

	#1	#2	#3
Total Suspended Solids.	4	4	6
(mg/l)			
Total Dissolved Solids.	235	304	410
(mg/l)			
Turbidity.3	.32	.6
(NTU)			
Sulfate.	4.0	6.8	19.8
(mg SO ₄ /l)			
Specific Conductance	390	490	610
(micromhos/cm)			
pH	7.5	6.7	7.9
Fluoride	0.1	5.4	0.12
(mg/l)			
Total Phosphorus	0.035	0.21	0.3
(mgP/l)			
Nitrates	0.06	0.04	0.35
(NO ₃ -Nmg/l)			
Kjeldahl Nitrogen.	0.1	0.1	0.1
(mg/l)			
Ammonia	0.1	0.1	0.1
(NH ₃ -Nmg/l)			
Oil & Grease.		5	
(mg/l)			

Table 3. Surface and groundwater chemical analysis.

	#5	#6
Total Suspended Solids.	3	6
(mg/l)		
Total Dissolved Solids.	278	132
(mg/l)		
Turbidity37	.81
(NTU)		
Sulfate	13.2	15.5
(mg SO ₄ /l)		
Specific Conductance	440	200
(micromhos/cm)		
pH	8.0	7.7
Fluoride	0.76	0.12
(mg/l)		
Total Phosphorus	0.095	0.03
(mgP/l)		
Nitrates.	0.01	0.12
(NO ₃ -Nmg/l)		
Kjeldahl Nitrogen.	0.1	0.1
(mg/l)		
Ammonia	0.1	0.1
(NH ₃ -NMG/l)		
Oil & Grease	5	
(mg/l)		

Table 3., (continued)

	#4	#7	Units
pH.....	7.4	7.0	
Total Alkalinity as CaCO ₃	286	358	--mg/l---
Phenolphthalein Alkalinity.....	0	0	
Calcium.....	75	99	
Magnesium.....	19	24	
Total Hardness as CaCO ₃	266	346	
as gpg.....	15.6	20.2	
Total Iron.....	0.04	0.07	
Sulfate.....	11	13	
Nitrates.....	0.05	0.07	
Potassium.....	11.7	11.7	
Sodium.....	6.9	6.9	
Chloride.....	3	6	
Arsenic.....	0.0005	0.0005	
Barium.....	0.2	0.3	
Cadmium.....	0.001	0.0011	
Chromium.....	0.02	0.02	
Fluoride.....	3.8	1.1	
Lead.....	0.01	0.01	
Manganese.....	0.09	0.03	
Mercury	0.0002	0.0002	
Selenium	0.005	0.005	
Silver.....	0.005	0.005	
Zinc.....	0.01	0.21	
Total Solids.....	324		
Turbidity TU.....	1.3		
Specific Conductance.....	515	605	
Oil & Grease.....	5		

Table 3. (continued)

	#74	#96	#130	#131
Calcium	80.0	22.6	18.7	46.0
Magnesium	17.4	5.83	23.5	18.5
Potassium	15.0	6.0	24.5	24.5

Table 3. (continued)

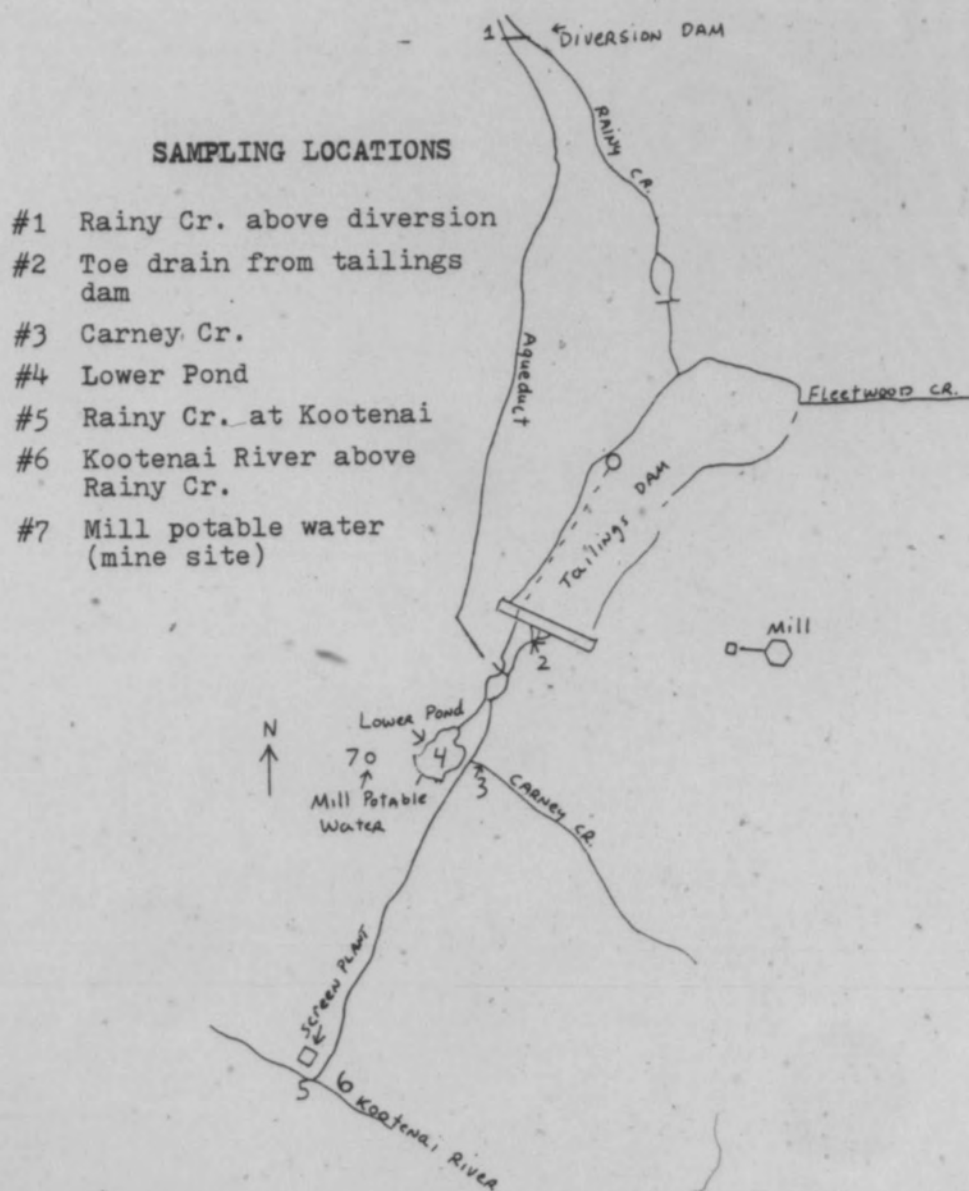


Figure 24. Location Map for Water Samples 1-7.

erosion can be expected seasonally. The pH ranged from 6.7 to 8.0 which falls within the normal range. The calcium content was as high as 99 mg/l which explains the hardness of the water. Fluoride concentrations were noticeably high in samples 2 and 4 of the tailings system.

The origin of the ore body "vermiculite" may be intrinsically related to the groundwater chemistry at the time of formation. Potassium, magnesium, and calcium were the principle cations exchange in the conversion of biotite to "vermiculite". It was thus essential to analyze the concentration of surface water and groundwater for these cations. The concentrations of these cations were not assumed to ultimately reveal the exact groundwater conditions at the time of formation but they should give some indication of the elements within the surface water and shallow groundwaters in the area. A further discussion of calcium, potassium, and magnesium concentrations and their effect on groundwater induced weathering will be made later in this thesis.

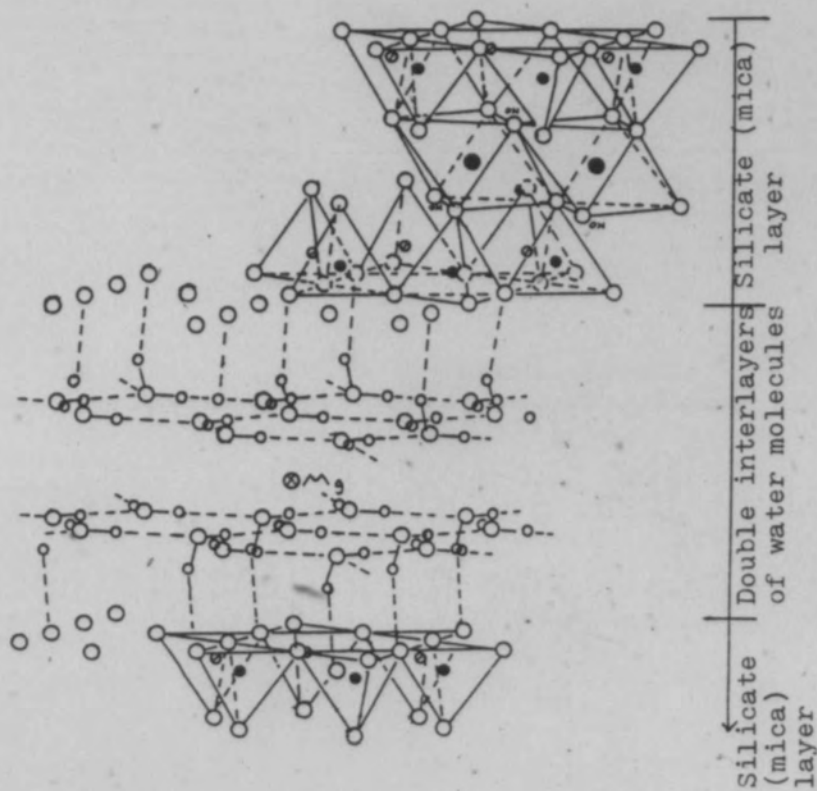
GROUNDWATER VERSUS HYDROTHERMAL GENESIS OF VERMICULITE

Vermiculite - General

True vermiculite is a micaceous mineral with a ferromagnesium-aluminum silicate composition. Vermiculite has perfect basal cleavage, crude density of 100 lb/ft^3 , hardness of 1.5-3.0, specific gravity of 2.3-2.8 and a melting point between $2425\text{-}2480^\circ\text{F}$. Vermiculite exfoliates upon heating because of the conversion of interlayer water to steam, forcing the laminae apart.

"Vermiculite" is the alteration product of micas, pyroxenes, amphiboles, olivine, and serpentine. The alteration in most cases includes an intermediate mica stage. At the Rainy Creek deposit vermiculite is the alteration product of biotite.

Structurally, vermiculite is a trioctahedral mineral composed of a tetrahedral-octahedral-tetrahedral repeating unit. These repeating units are separated by a 4.98\AA interlayer (Gruner, 1934) composed of water and exchangeable ions (Figure 25). The alteration of biotite to vermiculite is accompanied by the replacement of interlayer potassium ions with magnesium ions and the addition of approximately eight weight percent interlayer water. The transformation is also accompanied by an expansion along the "C" crystallographic axis from 10\AA to 14\AA . The change in Fe from the ferrous to the ferric state is believed by some to be



○○ ○_{OH} OH ● Al, Fe, Mg (octahedral sites)
 ⊗ Mg (interlayer) OH ○ and ● Si, occasionally Al

Figure 25. Diagrammatic Sketch of the "Vermiculite" Structure Showing Layers of Water (Bush 1976).

an integral part of the biotite alteration.

Hydrobiotite is also considered to be an alteration product of biotite. Hydrobiotite is composed of alternating layers of biotite and vermiculite and thus contains about half the weight percentage of water as does true vermiculite.

"Vermiculite" is valued for its unique property of exfoliating upon being heated. The Latin word "vermicular", meaning to breed worms, was given to this mineral because of the expanded worm-like pieces. The expansion is perpendicular to the cleavage and in the laboratory it can be expanded as much as thirty times its original thickness. Commercially, the highest volume change is about twenty times, with eight to ten being the most common. After considerable research commercial expansion was found to be optimum at 2000°F when heated rapidly. After expansion the "vermiculite" has a silvery to golden color and a dramatic density decrease to approximately 5-10 lb/ft³.

The major uses of "vermiculite" are for plaster and concrete aggregate, for soils in the agricultural industry, and for thermal insulation. Expanded "vermiculite" has low thermal, electrical, and acoustical conductivities. It is refractory, does not react with weak inorganic acids or bases and has an inert composition. It has also been used in chicken, swine, and dog feeds, printing inks, cat litter, and in numerous other ways.

Because "vermiculite" has such a low density when expanded it is not economically viable to ship the expanded product from the mine. For this reason there are fifty-one expanding plants situated in 33 states. Crude "vermiculite" is currently selling for approximately \$83/ton.

Other "Vermiculite" Deposits

"Vermiculite" deposits are widely distributed throughout the United States and the rest of the world. The United States is the largest producer and consumer of "vermiculite" in the world. The mine in Montana is by far the largest producer of "vermiculite". The following is a summary of some well known "vermiculite" occurrences other than the one at the study area.

The Gold Butte "Vermiculite" deposits occur in altered ultramafic rocks of Precambrian age (Leighton, 1967). Peridotites and perknites have intruded migmatites and other hybrid gneisses. The intrusion of the ultramafics is believed by Leighton (1967) to have formed the elliptical dome where the ultramafic rocks are centrally outcropping. The "vermiculite" occurs as veins, stringers, pockets, and as scattered flakes in the ultramafic rocks.

The Palabora igneous complex is located in the Archean Shield of northeastern Transvaal, South Africa. This deposit is ranked as one of the largest in the world. The complex hosts economic deposits of copper, magnetite, uraninthaite, baddeleyite, apatite, and "vermiculite". The igneous

complex resulted from an alkaline intrusive cycle which emplaced pyroxenite, syenite, and ultrabasic pegmatoids in succession. Hydration of phlogopite in the ultramafic core was responsible for the economic deposits of "vermiculite" (Palabora Geological and Mining staff, 1976). This deposit is in many ways similar to the one in the Rainy creek area.

The "vermiculite" in the North Carolina deposits, as described by Hunter (1949), is associated with dunite, saxonite, and pyroxenite lenses and dikes. The "vermiculite" occurs as interior and border veins varying in width from a few inches to 20 feet. The interior veins and lenses occur in small fault zones and small fractures. The "vermiculite" is believed to have a clear genetic history according to Hunter (1949). Hydrothermal solutions are believed to have altered the olivine or pyroxene to serpentine. The altering solutions permeated the basic rocks through fractures and joints set up by stresses in the rocks. Additional hydrothermal solutions then altered these minerals further to micaceous minerals which were then altered to "vermiculite".

"Vermiculite" deposits occurs in the Piedmont area of South Carolina. The deposits are in contact with biotite gneiss, schist, and granite. The "vermiculite" occurs in the upper weathered portion of biotite lenses that were at one time composed of pyroxenite (Hunter, 1949).

Previous Studies of "Vermiculite" Genesis

There exist basically three explanations for the genesis of the mineral "vermiculite". Those favoring a weathering origin are in the majority but a hydrothermal and hydrothermal-weathering origin are still favored for some deposits.

The following describes field and laboratory observations at "vermiculite" deposits throughout the world. It was the intent of the author to evaluate these observations with the hope of gaining some insight to the Rainy Creek deposit.

Field Studies

The second largest "vermiculite" deposit in the world is located at the Palabora Mine in the Republic of South Africa. The Palabora deposit is similar in many respects to the one at Rainy Creek, both of which are associated with ultramafic rocks. The Palabora deposit as described by their geological and mineralogical mine staff (1976) consists of two "vermiculite" bodies in the northern and southern parts of the ultramafic core. Although the southern deposit was recognized first, the northern deposit has produced the majority of "vermiculite" from Palabora. The mine staff has proved conclusively that "vermiculite" is a weathering alteration of phlogopite, a mineral similar to biotite. The hydrologic properties at the deposit,

namely the permeability, porosity, jointing and fissuring, have allowed hydration of the phlogopite in the 50 ft. zone of weathering. All degrees of weathering are found from fresh purplish phlogopite to purplish-yellow "vermiculite" (Palabora Geological and Mining Staff, 1976).

"Vermiculite" in the southeastern states is also thought to be a supergene weathering phenomenon produced by circulating meteoric waters in the zone of weathering. Bush (1976) believes these organic solutions circulated along weak zones altering chlorite to "vermiculite". Mining in the area has shown that the "vermiculite" only extends down through the zone of weathering which is commensurate with the depth of the local drainage. Only where structural features allow this free circulating water to penetrate deeper is "vermiculite" found below local creek levels. One particular example is at Corundum Hill, in Macon County, North Carolina where "vermiculite" grades into chlorite at the lower limit of free water circulation. The gradational zone is approximately 15-20 ft. deep and usually contains poor quality ore that is closer to the color of chlorite and requires a high temperature for exfoliation. Some of the larger crystals near the chlorite contact have been completely converted to "vermiculite" on the top side while the bottom side remains unaltered chlorite (Hunter, 1949).

Hunter (1949) describes the South Carolina deposits as similar to the North Carolina ones. The biotite contact

below the zone of weathering is unusually irregular. This is a result of changes in fracture density controlling permeability along the contact. Hunter (1949) also describes round, egg-shaped, or oblong lenses of biotite above the weathering contact that are completely surrounded by "vermiculite". These lenses probably contain few fractures and were resistant to the meteoric waters that controlled the altering process. Drilling data indicate that the deposits extend to about 80 ft. before biotite is encountered (Hunter, 1949).

Leighton (1967) has proposed a hydrothermal origin for the vermiculite deposit in Clark Co., Nevada. Leighton proposes that hydrothermal solutions associated with abundant granitic pegmatites accomplished the vermiculization. He also states that meteoric waters probable continued the alteration after the rocks had been exposed by erosion. Evidence sited for the hydrothermal origin includes zoning relations where pure vermiculite is associated with hydrothermally altered rocks and pegmatites. Evidence for a weathering origin can be seen under a microscope where in some vermiculite flakes the penetration of water is evidenced by the trace of oxidation left behind.

Laboratory Studies

The first mineralogist to show that vermiculite is a distinct mineral with a definite crystal structure

was Gruner (1934). The structural formula presented by Gruner was $(\text{OH})_2 (\text{MgFe})_3 (\text{Si,Al,Fe})_4 \text{O}_{10} \cdot 4\text{H}_2\text{O}$. He proposed the old term hydrobiotite, previously used to designate a hydrated biotite, for a 1:1 interstratification of biotite and vermiculite. It was obvious to Gruner that K could not be removed without an accompanying charge imbalance. He suggested the negative charge was neutralized by the oxidation of Fe^{2+} to Fe^{3+} or by the introduction of H^+ . He also suggested as another possibility the substitution of F^- or OH^- for O^{2-} . He stated there is usually not enough Fe^{++} to compensate for the loss of K and introduction of H_2O molecules.

Barshad (1948) initiated vermiculite ion exchange experiments and found vermiculite to have a high base exchange capacity, the exchangeable bases being Mg exclusively or Mg and Ca. He produced vermiculite by leaching hydrobiotite with a MgCl_2 solution and by prolonged treatment of biotite with a MgCl_2 solution he produced a material closely resembling vermiculite. There was now experimental evidence suggesting that a weathering process was responsible for vermiculite genesis. More importantly, Barshad had introduced a vermiculization process independent of the iron content of the parent mica. The exchange of K by Mg and H_2O retains charge balance and affects the interlayer structure only. Oxidation may occur but is regarded as a separate reaction.

Stability studies of vermiculite under hydrothermal conditions was undertaken by Roy and Romo (1957). Above 300°C they found a redistribution of Mg in the vermiculite layers and a "chlorite-like" mineral was formed. It was therefore clear to Roy and Romo that vermiculite could not have formed even in a mild hydrothermal environment (probably not above 200°C) and must have been derived by a low temperature reaction. All the samples analyzed by Roy and Romo were high in iron and they state that no well-authenticated case of true phlogopite (Fe-free biotite) weathering to vermiculite is known. They, like Gruner, believed the vermiculization process is from the leaching of K^+ and oxidation of Fe^{2+} , but also believed magnesium migrated from an octahedral position to an interlayer position.

The Libby deposit in particular was the subject of Bassett's (1959) work. Bassett furthered Barshad's (1948) ion exchange research and showed that vermiculite can be produced by placing biotite in solutions of .001 molar $MgCl_2$ or $CaCl_2$. His ion exchange experiments also showed K fixation takes place when the K concentration exceeds .04 molar, even when the Mg concentration is 1 molar and the temperature is 100°C. Bassett was unsuccessful in producing hydrobiotite by immersion in magnesium and calcium solutions but did produce a copper hydrobiotite in molar cupric chloride at 100°C for 100 hours. The mechanism

offered by Bassett for the formation of the 1:1 interstratification was the alteration of weak and strong bonds between the layers caused by a selective exchange for K by Mg and Ca. Bassett also postulated at the Libby deposit that biotite was formed from augite at the time of the intrusion of the syenite dikes. He thought biotite altered to hydrobiotite and vermiculite by supergene solutions.

Boettcher (1966) concluded from his ion exchange and hydrothermal experiment that the maximum upper limit of stability of vermiculite is about 350°C from 1-5Kb pH_2O . Boettcher (1966) suggested that his and previous ion exchange experiments are dissimilar to processes that formed natural vermiculite. He points out natural vermiculites have $\text{Fe}^{3+} > \text{Fe}^{2+}$ which was not observed in the previous experiments. In experimental agreement with Roy and Romo's postulation that Mg ions migrate from the octahedral layer to the interlayer, he suggests that leaching of K^+ and oxidation of ferrous ions reflect the natural alteration more closely than simple replacement of K. Boettcher (1966) was unsuccessful in producing a hydrobiotite and pointed out the copper hydrobiotite produced by Bassett (1959) contains OH ions rather than H_2O in the interlayer position and would thus resemble chlorite more than vermiculite.

Hydrobiotite and vermiculite were produced by weak

and strong magnesium sulfate solutions (Hoda and Hood, 1972). Hoda and Hood concluded from their ion exchange experiments that Fe rich micas tend to form 1:1 mixed layer structures in weak solutions whereas magnesium rich biotites and phlogopites alteration alter to vermiculite. It is thus concluded by the writer that Fe favors the biotite alteration to hydrobiotite. As evidence for this conclusion Farmer and Wilson (1970) believe oxidation of Fe^{2+} on either side of the hydrated interlayer would lead to stronger retention in alternating layers favoring the formation of hydrobiotite. Hydrobiotite is thought by Gilkes and Suddhiprakarn (1979) to be weathering product of biotite in southwestern Australia, but they also believe biotite weathering is clearly more complex than laboratory experiments reveal. They point out that while in laboratory experiments biotite alters to vermiculite or mixed layer clay minerals, the products of natural weathering may also be kaolinite, halloysite, illite, smectite, chlorite, and sesquioxides.

Present Studies of "Vermiculite" Genesis

Geochemistry

With the majority of literature favoring a weathering environment for the genesis of "vermiculite", chemical analyses and electron microscopy leaching studies were undertaken. Three samples from two shallow drill holes each (76 and 102) and six samples from a deep hole (130) were collected for the study. If leaching or ion migration in

the permeable surface zone had taken place, then a correlation between depth and ion concentration might be seen in these holes.

For comparison of the oxide concentration of vermiculite, hydrobiotite, and biotite from surface outcrops, reference is made to Table 4. From the table, the following comparisons are made between vermiculite and biotite: SiO_2 , Al_2O_3 , and total Fe are not significantly different between the two. The differences in MgO are small when calculated H_2O and K_2O free. Na_2O is absent in the vermiculite; McLaughlin (1955) reports Na is readily removed during leaching. There is a significant increase in K_2O from vermiculite to biotite. Fe has been converted to the ferric state, but total Fe remains about the same. The relationship between hydrobiotite and biotite is less clear, but the following inferences are made: K_2O concentration is less than half in the hydrobiotite, Na_2O is considerably higher in the hydrobiotite when compared to the K_2O concentration, CaO is higher in hydrobiotite than in the vermiculite and biotite combined, and the oxidation state of hydrobiotite is higher than in biotite.

The three samples from hole 102 were taken from depths of 10-20 feet, 130-140 feet, and 170-175 feet. Biotite pyroxenite is at 110 feet and the static water level is interpolated from surrounding holes to be at 85 feet. Figure 27 shows the results from the electron microscope

	RCSa-59 vermiculite	RC-Level 12 vermiculite	RCSp-49 hydrobiotite
SiO ₂	35.57	35.43	35.60
Al ₂ O ₃	11.47	11.30	11.85
TiO ₂	1.06	0.91	1.13
Cr ₂ O ₃	0.18	0.26	0.03
Fe ₂ O ₃	7.49	6.65	10.28
FeO	0.34	0.27	0.81
NiO	0.02	0.01	0.00
MnO	0.06	0.05	0.08
MgO	22.57	23.56	20.17
CaO	0.73	0.39	1.44
SrO	0.01	0.01	0.005
BaO	0.10	0.03	0.17
Na ₂ O	0.00	0.00	0.16
K ₂ O	0.96	0.14	3.17
Rb ₂ O	0.00	0.00	0.0129
Cs ₂ O	---	---	0.00041
H ₂ O ⁺	9.01	9.47	7.56
H ₂ O ⁻	10.11	11.26	7.20
P ₂ O ₅	0.06	0.05	0.07
F	---	---	0.21
OF			99.95 - 0.09
Total	99.74	99.79	99.86

Table 4. Chemical Analysis of Biotite, Hydrobiotite, and Vermiculite. (Boettcher 1966)

	RCSp-49 Hydrobiotite	RCB-12 biotite	RCSp-55 biotite
SiO ₂	36.77	38.63	39.10
Al ₂ O ₃	11.60	13.08	13.30
TiO ₂	1.02	1.55	1.21
Cr ₂ O ₃	0.27	0.23	0.25
Fe ₂ O ₃	8.19	2.50	2.56
FeO	0.98	8.75	7.23
NiO	0.01	0.02	0.02
MnO	0.08	0.14	0.10
MgO	20.04	19.94	21.55
CaO	1.94	0.18	0.12
SrO	0.01	0.005	0.005
BaO	0.19	0.45	0.35
Na ₂ O	0.12	0.26	0.23
K ₂ O	3.84	10.00	10.05
Rb ₂ O	0.0158	0.04	0.03
Cs ₂ O	0.00050	---	---
H ₂ O+	6.69	3.52	3.74
H ₂ O-	7.80	0.30	0.06
P ₂ O ₅	0.06	0.06	0.00
F	0.30	0.30	0.35
O F	99.93 - 0.12	99.95 - 0.12	100.26 - 0.18
Total	99.81	99.83	100.08

Table 4 (continued)

(see Figure 26 for the key).

The chief dissimilarities in ion concentration in hole 102 are seen in the K, Ca, and Fe peaks. K concentration increases significantly down the hole, corresponding to a higher mineral content of biotite in the biotite pyroxenite. The highest concentration of Ca was found in the deepest sample. According to Table 4, this would correspond to a platy mineral assemblage highest in hydrobiotite. The second highest Ca content was in the near surface sample where the highest quality of "vermiculite" was found. Although total iron should be almost constant, there was a decrease in iron in the deepest sample. It is thus postulated, that Ca replaced Fe ions in this sample.

The biotite pyroxenite in hole 76 is very shallow (approximately 40 feet). The small vermiculite pyroxenite interval was reflected in the electron microscope results. Figure 28 shows no dissimilarity existed between any of the ions. The high K concentration leads the author to believe all the platy minerals were of friable or poor quality.

The biotite pyroxenite contact in hole 130 was at a depth of 25 feet. Figures 29 and 30 show the electron microscope results for the six samples taken at intervals of 0-10 feet, 40-50 feet, 140-150 feet, 400-410 feet, 760-770 feet, and 890-900 feet. Chemical analyses of these

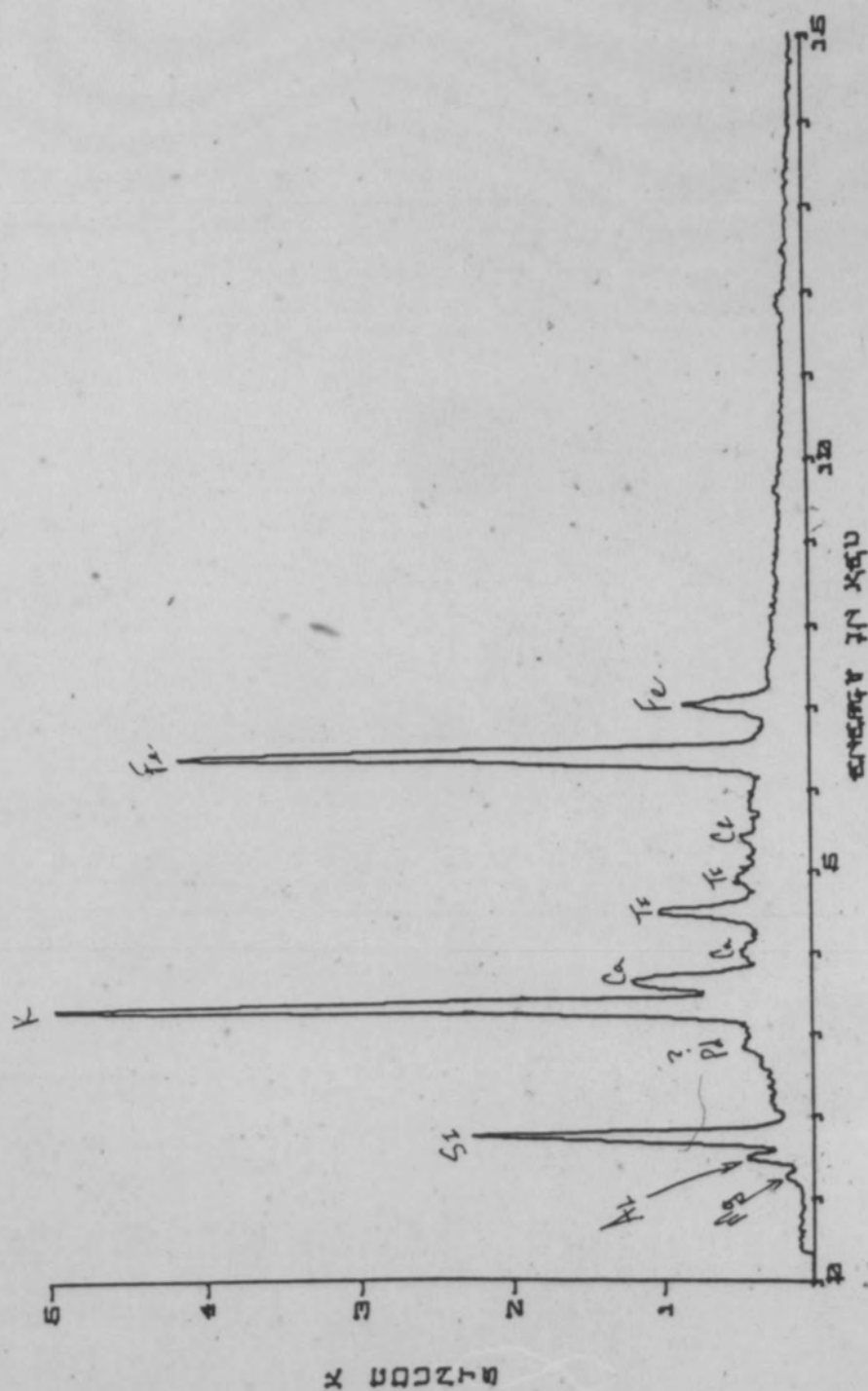


Figure 26. "Key" for Electron Microscope Analysis

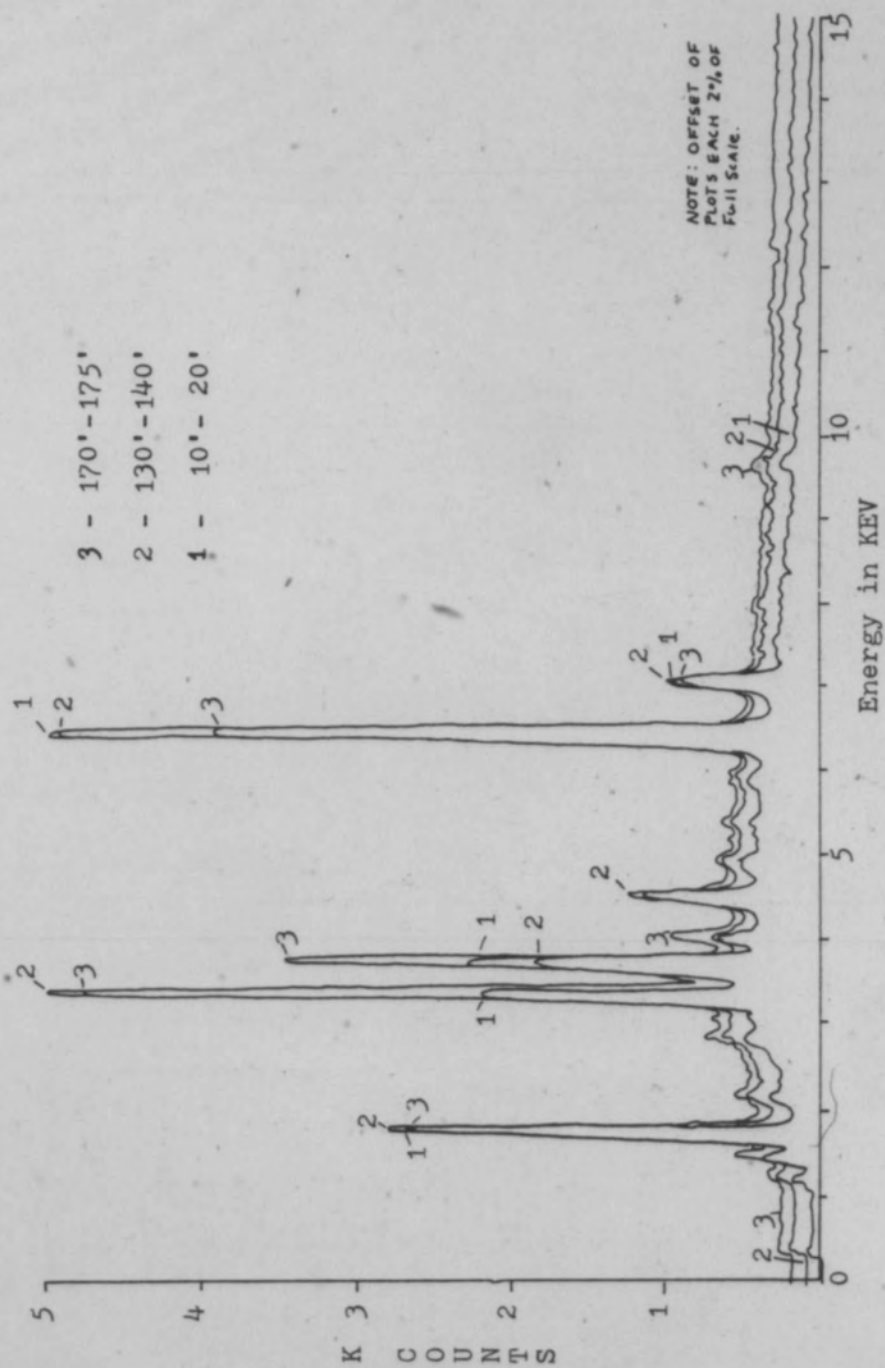


Figure 27. Electron Microscope Analysis,
Hole 102.

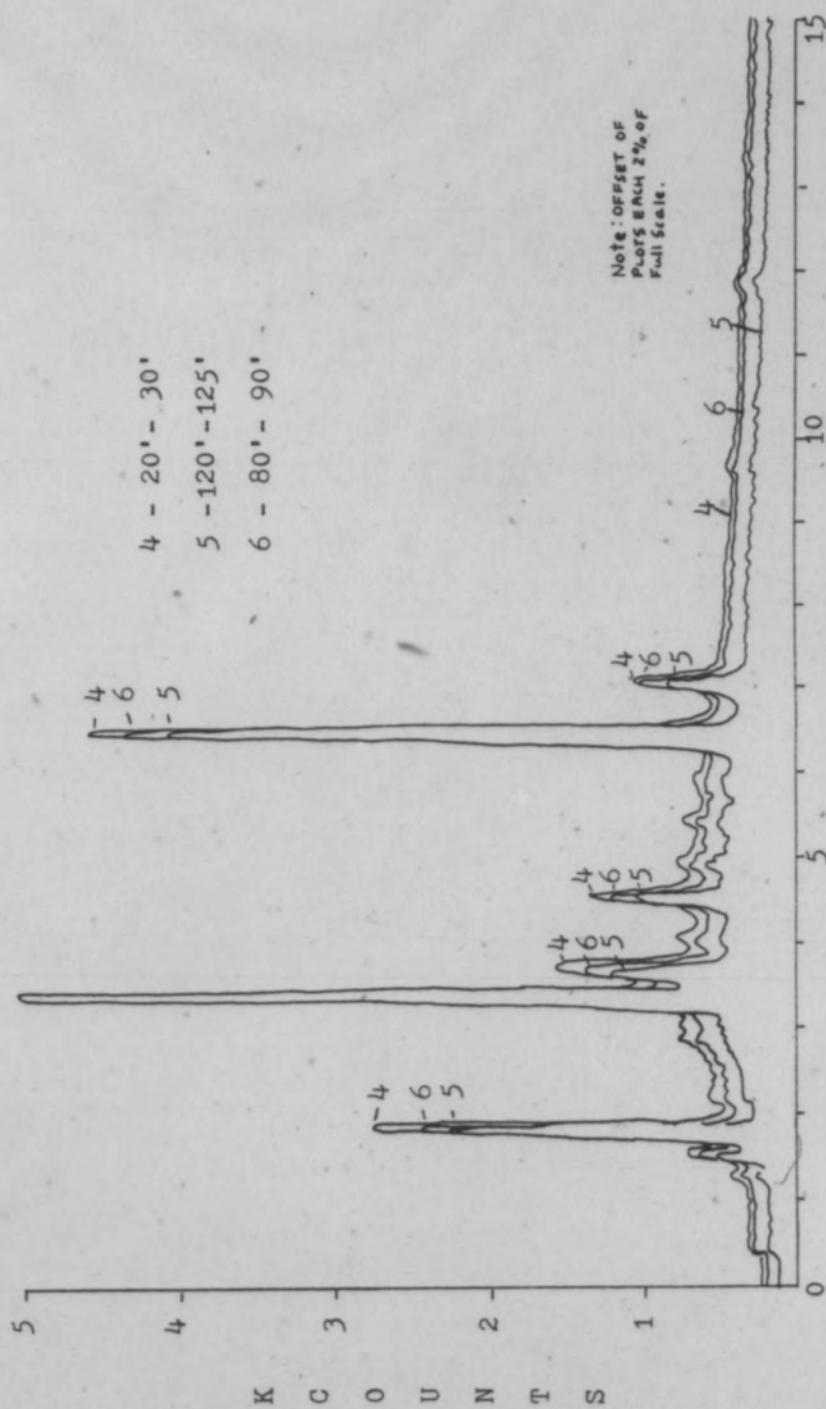


Figure 28. Electron Microscope Analysis,
Hole 76.

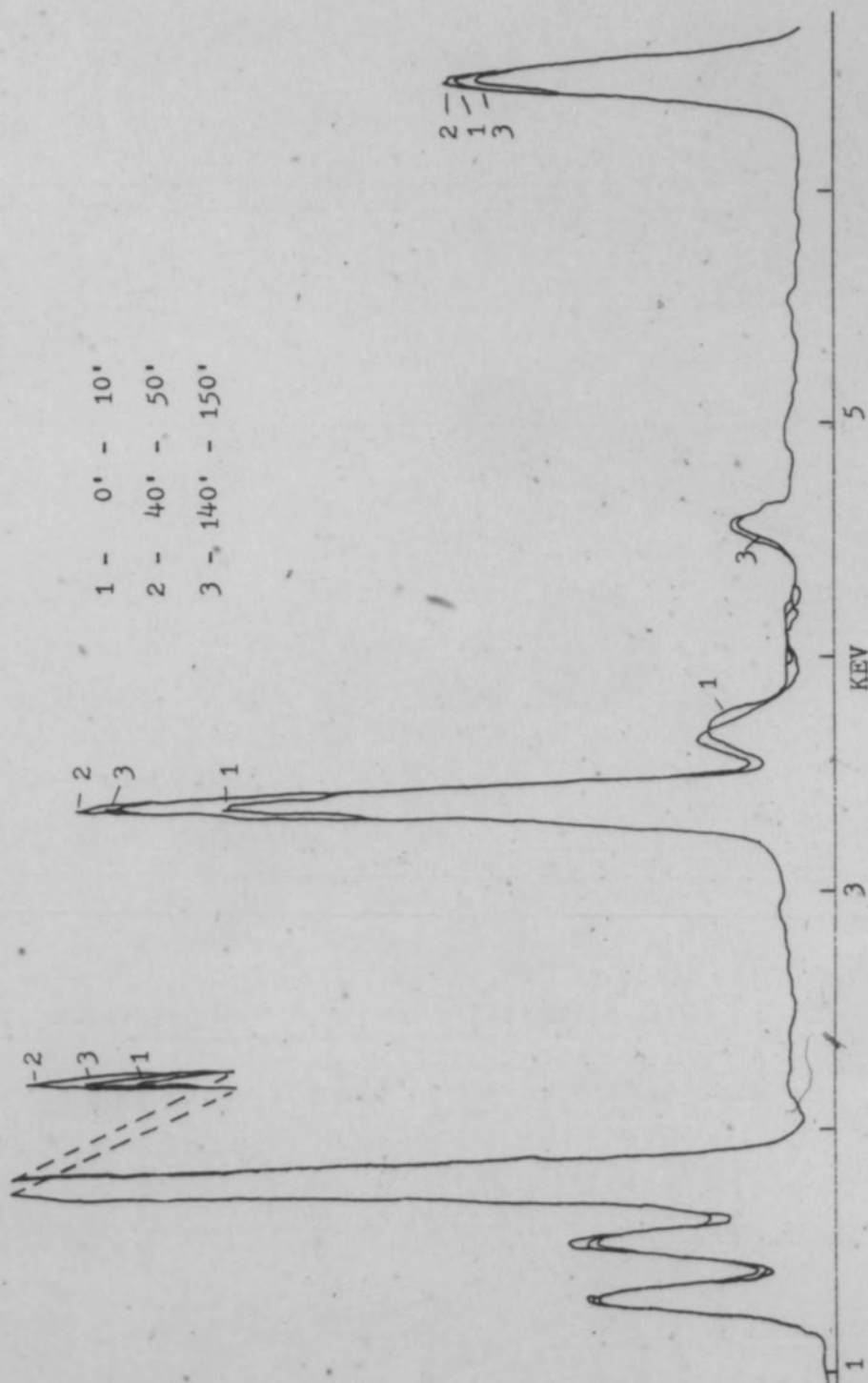


Figure 29. Electron Microscope Analysis, Hole 130.

samples were also made and the results are shown in Table 5. The greatest noticeable change in ion concentration was the increase in K. There was also a slight increase in Si. Both these changes are also seen in Table 5. Because total ion concentration was only 90.39% in the 0-10 feet sample, 9.61% is approximated as the water content. Similarly calculated, the water contents for the remaining holes were considerable less as would be expected.

Hydrochemistry

To introduce field evidence to support the previously discussed laboratory results of Gruner (1934), Barshad (1948), Roy and Romo (1957), Bassett (1959), Boettcher (1966), Hoda and Hood (1972), etc., the author took groundwater samples from four different locations in the mine area (holes 130, 131, 74, 97). The samples were analyzed for K, Mg, Ca because they were the principal ions used by the above researchers in their ionic alteration solutions. The results of the analysis, along with those furnished by mine personnel, have been listed previously in Table 3.

None of the potassium concentrations exceeded the fixation level of 1564 mg/l (.04 molar), clearly indicating there is presently no inhibiting effects on the alteration of biotite to hydrobiotite or vermiculite.

SAMPLE TYPE :
PULP

SAMPLE	SI02 %	Al2O3 %	FE2O3 %	CAO %	MGO %	NAO %
81-130						
0-10	45.5	11.1	8.1	.99	15.2	.54
40-50	19.5	12.2	9.	.58	16.5	1.17
140-150	51.5	11.1	8.3	.86	17.4	.7
400-410	48.	11.1	8.	1.51	15.2	.59
700-770	50.	11.7	9.4	.53	15.7	.97
890-900	46.5	10.9	8.7	1.33	15.2	.47

SAMPLE TYPE :
PULP

SAMPLE	BA PPM	CR2O3 PPM	K2O %	MNO %	TI02 %
81-130					
0-10	2230.	409.	7.9	.06	1.
40-50	2620	394.	11.1	.06	1.05
140-150	2040.	292	10.9	.07	1.01
400-410	2300	445.	10.2	.06	.95
760-770	2950.	277.	11.3	.07	1.08
890-900	2450	306.	10.7	.06	.96

Table 5. Chemical Analysis of Hole 130.

Furthermore, the lowest concentration determined to produce vermiculite in the laboratory was a .001 molar (24.3 mg/l) solution of MgCl_2 . All the concentrations of Mg in Table 3 are less than 24.3 mg/l, indicating that at least some of the interlayer Mg in "vermiculite" must have migrated from the octahedral sites, as was postulated by Roy and Romo (1957). The idea of Mg migration is an important concept because a large source of Mg was a serious problem where some weathering origins have been proposed (Boettcher 1966).

In general, groundwaters from mafic and ultramafic rocks, gneisses and schists, and dolomites favor the weathering alteration of biotite to "vermiculite". Typical magnesium and potassium contents of groundwaters from the above rock types and granite are given in Table 6. Groundwaters from mafic and ultramafic rocks and dolomites have high magnesium contents, but little potassium. Granites yield waters that have low magnesium and high potassium contents. Groundwaters from gneisses and schists have concentrations in between these extremes with moderate magnesium and potassium contents (Hoda and Hood, 1976). It may be recalled that nearly all "vermiculite" deposits occur in mafic and ultramafic rocks and in gneisses and schists. Even in severe weathering of granite, biotite does not commonly alter to "vermiculite".

When Hoda and Hood (1976) plotted the average ground-

Rock Type	Magnesium content			Potassium content		
	High (ppm)	Average (ppm)	Low (ppm)	High (ppm)	Average (ppm)	Low (ppm)
Granitic rocks	14	6-3	2-6	14	4-1	0-8
Mafic and Ultramafic rocks	76	27-2	2-6	3-2	1-5	0-0
Gneisses and Schists	57	15-8	0-7	5-8	2-7	0-4
Dolomites	86	51-2	14	3-5	1-8	0-6

Table 6. Magnesium and Potassium Concentrations in
Groundwater. (Hoda and Hood, 1976)

water contents of potassium and magnesium on their stability diagram, mafic, ultramafics, gneisses, schists and dolomites plotted in the field of easily altering micas, while groundwaters from granitic rocks, plotted in the mica field. Thus, it must be concluded that even though a source of Mg is not required to produce "vermiculite" in the laboratory, Mg rich environments definitely favors vermiculite.

As a word of caution, it must be remembered that the analyses only reflect present conditions. It is hoped that these conditions are not significantly dissimilar to those in the past and that they may add some understanding to the questions raised here.

Mechanisms of Alteration

In the section covering the geology of the igneous complex, it was revealed that the depth of alteration in the "vermiculite" pyroxenite averaged 150-200 feet. Furthermore, there exists a centrally located unaltered biotite pyroxenite that extends from the surface to an undetermined depth. This unaltered zone was exposed before mining began which raises interesting questions in regard to the mechanism of alteration.

From a weathering viewpoint, one would expect to find a weathered zone at the surface and an unaltered zone at depth. The depth of alteration depending on the depth of

the local water table and accessibility of altering fluids in the zone of aeration.

Why the central zone of biotite "vermiculite" was not altered in the same manner as the rest of the biotite pyroxenite is somewhat puzzling. Boettcher (oral communication) suggested that the high content of biotite in this zone may have been responsible. He states the high biotite content might have poisoned the alteration reaction because of the high amount of potassium available (K fixation). If this was the case, then no base ion exchange reactions could occur and the alteration of biotite would be resisted.

However, if one assumes "vermiculite" was formed from biotite then biotite poisoning in this case is not plausible because there are certainly areas of the mine that run as high as 70-80% "vermiculite" content by weight that must have at one time been biotite.

An alternate interpretation as to why there exists such a substantial physical difference between these two zones was proposed by mine personnel. It was suggested that an erosional and/or mountain building episode was responsible for the segregation of altered areas. This would also explain why the altered zone is so mechanically disintegrated and friable. The biotite pyroxenite would be eroded from the highest elevation on the ridge, continuously exposing fresh unaltered biotite pyroxenite in

the central zone. The end results would be an unaltered central zone surrounded by a mechanically broken up material and underlain again by unaltered biotite pyroxenite. The broken up material would then be permeable enough to allow percolating groundwaters to circulate through, converting the biotite to "vermiculite". Large block like pieces of altered biotite pyroxenite are reported in the main body of "vermiculite" pyroxenite. These blocks appear separate from the main mass and could very well fit into the above interpretation. The biotite pyroxenite eroded from the top of the ridge may have, in some instances, broken into large blocks and then slid down to their present position.

For this explanation to be plausible it must then be assumed that the vein and dike emplacement occurred after the uplifting and block faulting because the dikes and veins are not faulted.

Considering the above explanations, the writer believes the mechanical breakdown in the "vermiculite" pyroxenite is an insitu process. Whether the vermiculite pyroxenite was eroded off as explained above is presently only speculation. Weathering of the biotite by percolating groundwaters produced "vermiculite" with an accompanied expansion along the "C" crystallographic axis from 10\AA to 14\AA . This volume change was caused by a rearrangement of atoms with the addition of interlayer water.

This process probably produced a multitude of microfractures in the pyroxenite, causing it to mechanically disintegrate. This would also explain why the pyroxenite is so friable and soil like. While individual pyroxenite grain still retain a vitreous luster.

Expansion of mica minerals with an accompanying volume change is not a new idea. Wahrhaftig (1965) and others, have concluded that the expansion of biotite in contact with groundwaters is the chief weathering process in the Sierra Nevada Granodiorite. The deterioration is caused by microfracturing of the surrounding matrix. The weathering becomes so intense that very competent granitic rock weathers to a Grade 5 saprolitic rock.

The trace quantity of good quality "vermiculite" found in the two deep holes does not appear to be associated with a weathering process. This "vermiculite" is so deep and widespread that a process other than weathering must be postulated. It is thus concluded by the writer that dilute hydrothermal fluids may have been responsible for this small amount of alteration. The alteration taking place far below the weathering front within the unaltered magnetite pyroxenite and biotite pyroxenite.

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